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Susceptibility, vulnerability and averaged risk analysis for resilience enhancement of urban areas

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Abstract

The dynamic growth and evolution of urban areas generate new challenges for safety and security driving societal, economic and ecological developments at local and worldwide levels. Cities comprise a high degree of critical infrastructure with an increasing complexity and interdependency. In addition, modified and new threats ranging from natural to man-made and malicious hazards ask for more robust and sustainable cities. This work combines and extends existing empirical, engineering and simulative methods to define and determine quantities for resilience assessment of urban areas in a comprehensive approach. Based on a multitude of possible events in a city quarter with a larger number of infrastructures, susceptibilities, vulnerabilities and averaged risks are analyzed in a systematic and quantitative way. The use of an established empirical-historical database gives first insights to identify susceptible elements or endangered areas in the considered urban environments. It is coupled to an approach for consequences where state-of-the-art physical-engineering hazard and damage propagation and quantification models are integrated for vulnerability assessment. The consideration of multiple threats and multiple possible locations cumulates in an object-location-dependent quantification of averaged risks to visualize the most critical regions and infrastructure aspects in densely populated areas. In this article the approach is exemplarily applied to terroristic threats. The integration of the 3D-visualized approach into existing risk assessment and management processes will help to create cities that are more resilient.

Keywords: Urban vulnerability and weak points; explosive threats; multivariate distribution; quantitative risk and resilience

1 Introduction

1.1 Motivation

A steadily increasing number of the world's population is living in urban regions. 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]. The result is an increasing population and building density, which has a lasting effect on the vulnerability to hazardous events [2]. Agglomerated areas comprise a high degree of critical infrastructure, which builds the backbone ensuring the wellbeing of a society. As stated in [3], it is clearly observable that systems, cities and infrastructures will become more complex and interconnected. Due to this change, the failure of a single element can produce cascading effects with unexpected consequences [4]. Furthermore, there is a changing threat situation. According to Branscomb [5] cities are increasingly vulnerable to three kinds of disasters: natural disasters (e.g. hurricanes, flood, earthquakes, or tsunamis), technogenic disasters (resulting from human error and failing infrastructure, e. g. power failure) and terrorism.

Based on the facts of increasing urbanization, growing complexity and the presence of new threats, there is a need to evaluate possible hazardous events and the corresponding consequences. Aim is the generation of more robust and sustainable cities. Achieving sustainability requires the strengthening of resilience [6]. To reach this goal, concepts have to be developed, to reduce the probability of occurrence and the consequences from those events. Furthermore, these concepts should include on equal footing measures to be prepared, to response adequately, and to master recovery after a shock event [7]. Three of this aspects are also determined in [8] as the main abilities of a resilient system.

A generalized framework for quantification of resilience should give insights. There are frameworks available, to quantify the resilience of care facilities [9] or residential buildings [10]. Risk analysis methods are often used to identify the consequences [11] and the term risk is often linked to the terminology of vulnerability [12]. Measures to reduce the occurrence and impact of disasters will enhance the resilience of a city [13]. The characteristic to describe the weakness of a system, which is exposed to a threat, is sometimes understood as susceptibility [14].

Besides the assessment of urban environments, there are further fields of research, which are dealing with this terminology. The approach of Ball [15] evaluates the survivability of airplanes, for example. In this framework, the susceptibility and vulnerability of numerous components build the basis to assess a risk measure of the whole system. In alignment with Ball [15], the component-by-component assessment of a whole system and the consideration of multiple possible threat types and scenarios can be transferred for application to an urban environment. Metrics of susceptibility and vulnerability of single urban objects and infrastructure elements provide contributions for a comprehensive risk and resilience approach.

The publications [16], [17], [18] and [19] present an emerging mathematical approach for the integration of security issues into urban planning processes and give a first indication for weak spot identification in cities. Parts of the approach were first implemented in a demonstrator as a result of the research project VITRUV [20]. The main aim is to contribute to the resilience assessment and improvement of urban areas by defining and computing quantities to assess the level of prevention in terms of susceptibility, the level of protection in terms of vulnerability, and the preparation and response in terms of averaged risk. As far as possible, these measures use existing risk terms and quantities. Oriented to typical operational stages of urban planning, the comprehensive approach includes different levels from concept over plan to detail level [20].

The analysis on plan level uses mainly empirical-historical data to quantify expected losses in terms of averaged susceptibilities, vulnerabilities and risks [18], [19]. Due to the variety of possible hazard scenarios, there is much less statistically sound data available for specific consequence effects when compared to data on the occurrence of hazardous events [17]. Without further scenario specification, the statistical data provide information for single urban objects only and the interaction with the neighborhood, the structural building type and the physical access control are not considered. The empirical approach provides fast results and gives a first indication for urban environments. The historical data provide crude results concerning the consequence and vulnerability estimation. This also enters into the risk quantities.

For improved analysis of resilience in terms of averaged susceptibilities, vulnerabilities and risks, it is in the following recommended to go beyond historical-empirical data assessment as published in [17]. Based on physical accessibility, spatial threat and exposure distributions are used in addition for the susceptibility computations. The vulnerability evaluation uses hazard propagation and damage models, which are based on empirical-analytical physical and engineering formulations. First preliminary results of this approach was published in [16] and [18].

1.2 Selected Existing Approaches for Risk and Resilience Assessments

A review of existing frameworks gives an overview of the state of the art concerning the risk and resilience quantification of urban environments. Subsequently selected approaches are presented.

A comprehensive management process to protect most important infrastructure assets is the Risk Analysis and Management for Critical Asset Protection (RAMCAP) approach [21]. The procedure is a risk and resilience assessment scheme in seven steps: (1) Asset characterization, (2) Threat characterization, (3) Consequence Analysis, (4) Vulnerability Analysis, (5) Threat Assessment, (6) Risk and Resilience Assessment, (7) Risk and Resilience Management. The RAMCAP approach gives essential insights for risk and resilience assessment and management and helps to identify worst reasonable consequences. Resource allocation decisions are supported to reduce risk and to enhance resilience. The RAMCAP approach is based on the assumption that risk is defined as product of threat, consequences and vulnerability. The threat is defined as an event with potential to cause harm, vulnerability describes the weakness in an asset (the conditional probability that the threat leads to actual consequences) and the consequences are the outcomes of an event occurrence. In this interpretation, resilience is not an element of the risk equation but resilience assessment uses the outcome of risk assessment in combination with the economic loss to estimate the speed of returning to full functionality.

The RAMCAP approach differs from the present methodology, which quantifies and averages threats and vulnerabilities in the sense of RAMCAP within its susceptibility quantities. The consequences in the sense of RAMCAP differs in its vulnerability quantities taking into account multiple threats, threat locations as well as objects at risk. The present approach also assumes that for response and recovery new and novel quantities have to be defined that also take the time dependence of response and recovery measures into account. Resilience assessment is then envisioned to take into account all phases and corresponding quantities.

A similar definition of risk as in RAMCAP is used by the Federal Emergency Management Agency in the range of counterterrorism [22]. In this guideline, risk is influenced by the nature and magnitude of a threat, the vulnerability to that threat, and the consequences that could result from a successful threat. Nominal scales rather than quantitative approaches are applied for quantification. Analogue to the RAMCAP approach, the FEMA assessment evaluates the risk for a single scenario and a single object. The approach has to be evaluated manually for multiple threats and multiple objects, like city quarters.

A risk-informed decision support is published by Stewart [23]. In this article, the benefit of different countermeasures against terroristic threats are derived with risk assessments in alignment of multiple threat scenarios. Resilience indicators are implicit in the quantitative risk approaches, but the term resilience is not explicitly expressed in this publication.

Krawinkler and Miranda [24] present a performance based solution in the range of earthquake engineering. The semi-quantitative approach uses a probabilistic hazard analysis as input to evaluate the response of single buildings and can be interpreted as a closed quantitative risk assessment approach. With the definition of a performance target (e.g. collapse or life safety), this methodology relates engineering disciplines with decision-making risk management approaches. The generalized variables of intensity measures, engineering demand parameter, damage measures and decision variables are formally combined into one formulation to assess a performance-based solution in a probabilistic sense. The outcome is highly dependent on uncertainty correlation between damage measures (physical conditions of a structure) and decision variables (e.g. economic loss or life safety) for components within in given facility [25]. Summarizing, the performance-based approach is a powerful instrumentation, but the evaluation occurs for single items and terms of resilience are not considered.

Efforts of quantifying resilience are published by Bruneau, et al. [8] [9] and Cimellaro, et al. [26]. Performance-based risk formulations including engineering models are used to quantify possible losses. The approach is applied for the evaluation of acute care facilities exposed to seismic activities. Objectives in this methodology are the reduction of failure probabilities and the reduction of consequences from failures. Opposite to classical risk assessments, the framework aims also at the reduction in time to recovery. This approach gives first indications for a quantification scheme of resilience, but the attempted integration did not result in a single metric for different systems. Especially Cimellaro [26] achieved parts of the model by case-dependent assumptions.

A mixed semi-quantitative and quantitative resilience assessment procedure is published by Togkoz and Gheorghe [10]. In their work, single residential buildings are evaluated when subjected to hurricane winds. The proposed resilience formulation is applied for different threat categories and building types which are selected from HAZUS [27]. The damage is estimated with five different empirical damage categories and engineering models are not applied.

The overview of selected approaches shows the availability of existing frameworks for the quantification of expected losses. Single objects or single event scenarios are mainly evaluated. The present approach will evaluate whole city quarters with consideration of different urban objects. Due to the many different influence parameters, the presented methodology has to resolve the issue of how to take account of multiple possible hazard event positions, event types and intensities. The reduction in well-defined sets of events seems to be too simplifying. The approach in the present publication takes into account of these challenges using data-driven distributions for all uncertain data inputs as well as by averaging results. Some adequate risk assessments do not address the concepts of resilience management in all phases or apply assessment schemes with the use of pure statistical data. In summary, the following is currently missing which motivates the present work: a quantitative assessment of complete urban environments with the data-driven consideration of multiple threats and the application of physical consequence and damage models, as well as its contextualization in the resilience concept.

An extended comprehensive assessment scheme is defined to evaluate susceptibility, vulnerability and risk as far as possible avoiding statistical event data. The stepwise results of this assessment can be applied for estimation of expected losses and builds an input for resilience quantification. The procedure presented in this article is applicable to evaluate complete urban areas to identify weak spots in an arbitrary surrounding at different levels of detail in alignment with an urban planning process. The theoretical framework is applicable for all-hazard scenarios. Examples are shown for low-probability high-consequence events in the range of terroristic threats. The theoretical formulations of this article are currently implemented in a prototype software within the projects VITRUV [20] and EDEN [28]. The software aided approach allows a fast and efficient evaluation of weak spots at different levels of detail.

2 Generalized risk approach for the assessment of urban areas

The evaluation of hazardous events, in particular urban environments exposed to such threats require clear definitions of terms for the development of a generalized approach. Oriented to [13] and [29] the term resilience is understood as the ability “to prepare for, to prevent, to protect from, to respond to and to recover from as well as to adapt to actually or potentially adverse events”. Adverse events are human, technical and natural made disasters or processes of change with potentially catastrophic consequences [7], at least for subsystems. A resilient system includes at the minimum the three aspects of (1) reduced failure probabilities, (2) reduced consequences from failures and (3) reduced time to recovery [8], as well as (4) enhanced preparation status, (5) adequate response and (6) capability to learn from past events.

For the present work, the defined context of resilience is shown in Figure 1. Besides the phases prevention and protection, which are respectively covered by the susceptibility and vulnerability quantities, the preparation phase is supported with the averaged risk quantities. Also the response and recovery phase are supported by the vulnerability and risk assessment, since the expected and actual damage are an important input for adequate response and recovery. With Figure 1 it also becomes more explicit that the present approach does not claim to quantify the resilience performance in all phases.

Assessment quantities	Resilience management phases				
	Prepare	Prevent	Protect	Respond	Recover
Susceptibility					
Vulnerability					
Risk					
Resilience capabilities	e.g. sensing/ observing, modelling/ orienting, inferring/ deciding, acting/ responding, learning/ adapting				

Figure 1: Heuristic overview and relation of terms in the context of resilience assessment of urban areas: resilience management phases and their coverage with assessment quantities. Key risk assessment steps are susceptibility and vulnerability analysis. Reprehensive resilience capabilities cover all phases.

With respect to established definitions [30], [21], risk is in the present work defined as the combination of susceptibility quantities, namely the probability of occurrence of an event, the exposition to that event, and the consequences (damage effects) in case of event occurrence (vulnerability). To describe the weakness of a system by including the frequency of occurrence and the exposition to a threat by defining a susceptibility is as outlined in [14]. The term vulnerability is related to the consequences (damage effects) in case of occurrence. The conditional probability that the considered hazard event results in damage given the occurrence ot the threat event is interpreted as vulnerability. The present article also often uses the mean expected damage to express the vulnerability.

There are different damage types for evaluation, for example the number of affected people, structural or monetary damage. The five resilience phases and the corresponding need for quantitative assessment, namely prepare, prevent, protect, respond and recover are covered by different phases of the presented framework, see Figure 1. The matrix scheme indicates the effectiveness of the resilience indicators presented in this article, which is focused on the risk analysis quantities.

3 Key Defintions

An abstract model of an urban area U is the basis for the evaluation of expected losses. The superset U defines the urban area which is placed in a geographic region $G_h,\ h = 1, \dots, n_{geographic\ category}$, where $n_{geographic\ category}$ is the number of distinct geographic regions. U has a finite number of subsets, which describe single urban objects like buildings, traffic elements or open spaces.

A single urban object (uo) $b_k,\ k = 1, \dots, n_{uo}$ is given by a position $\vec{r}(b_k)$, a dimension $L(b_k)$ and a type of object use $u_l(b_k),\ l = 1, \dots, n_{ot}$. If b_k defines a building in the considered environment, $u_l(b_k)$will describe the usage of the building, for example residential or educational. Open spaces in the urban environment are divided into distinct geometric areas (ga) $a_m,\ m = 1, \dots, n_{ga}$, like plane polygons, for example. For simplicity, the later used second evaluation grid for susceptibilities, vulnerabilities and risks applied for the visualization of quantities on buildings and structures is not introduced explicitly. In summary, the urban environment is modeled as a set with

$$U = \left\{b_1, b_2, \dots, b_{n_{uo}}, a_1, a_2, \dots, a_{n_{ga}}\right\}. \tag{1}$$

The threat types exposed to the urban environment U are defined by $T_i, i = 1, \dots, n_{threat}$, where n_{threat} is the number of different types and intensities of threats considered within a scenario. A single threat T_i can have different possible event locations $\vec{r}_j,\ j = 1, \dots, n_{location}$ in the urban area. All grids are independent of each other.

In this work, risk is interpreted per definition as the sum of products of quantities relating to the frequency and exposition (susceptibility) and to the consequences (vulnerability) of hazardous events. For evaluation of an urban environment exposed to a threat, the frequency and consequence quantities are determined with the risk analysis scheme, which is shown in Figure 2. The methodology is oriented on insights from standardized risk approaches like the International standard for risk analysis and management [31], also employed in [16]. The risk quantities are assessed with a quantitative three-step method.

The first step, the (local and global, individual and collective) susceptibility analysis includes an empirical examination using historical data to quantify the absolute event frequency and historical data and expert estimates to assess the local distribution of event frequencies as well as exposition data for personnel. The second step uses in addition physical engineering and damage models for the quantification of (local and global, individual and collective) vulnerabilities. The third step combines the quantities to (local and global, individual and collective) risk quantities.

Figure 2 shows the generalized procedure for weak spot identification of urban environments exposed to hazardous events. Initially, the scenario and hence the context is defined. Characteristic information about the considered urban area is essential to build the basis for risk analysis. The region where the urban area is placed decisively influences the characterization of urban objects, like buildings, infrastructure elements and open spaces. Besides the spatial and geometry information the building usage and structural physical type enter. These input parameters are used in the further steps. Additional properties like population type, economy, ecology and governance that can decide on the risk and the vulnerability of single items and finally the resilience of the urban environment [32], [33] are not considered explicitly in the present historical data and engineering approach. The used empirical data have taken into account all these factors, since they use only historical events.

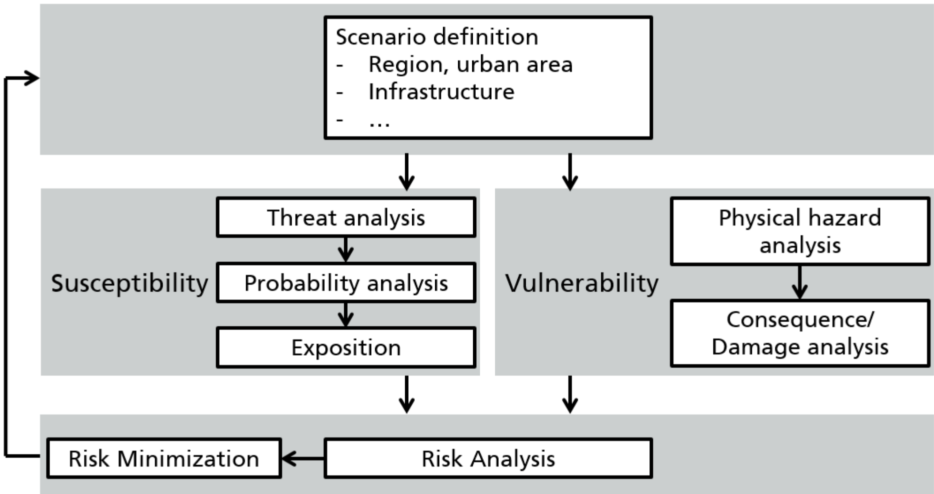

Figure 2: Scheme for susceptibility, vulnerability and risk analysis for urban areas to improve resilience. This article covers mainly the grey shaded boxes.

According to Figure 2, one essential step of the risk analysis includes the susceptibility assessment, which covers the quantification of the likelihood of hazard events. The results give information about the type, the frequency of occurrence and the intensity of different threat types at all relevant locations for the investigated quarter. With consideration of the urban environment, the exposition is a further essential parameter for susceptibility analysis. This step is purely dependent on probability sizes and the geo data.

The second step of risk analysis is the vulnerability assessment. The basis builds the physical characterization of the hazard source and intensity for a given threat type and the modeling of the hazard propagation. With a detailed characterization of urban objects, the next step delivers the quantification of physical consequences in case of occurrence. Finally, the damage response of the objects under the impact of the physical hazard potential determines the consequences (damage effects) and hence the vulnerability.

Combinations of susceptibility and vulnerability give insights to quantify the risk for a considered urban area exposed to a certain type of threat. Covering the whole area, the collective (group) risk evaluates the averaged damage if a threat scenario occurs. Related to a single object, the risk results can be used to assess if the results are acceptable or not using individual risk criteria. Possible enhancement measures can minimize the risk and an optional evaluation can be conducted in a frequency-number diagram [34].

Within the scope of the work, the key definition of averaged risk and its components reads

$$R = \sum_{k=1}^{n_{urban\ object}} S_k \cdot V_k \ , \ S_k := F_k, \qquad V_k := C_k. \tag{2}$$

Risk R is described as a sum of products of (averaged) susceptibilities S and (averaged) vulnerabilities V over all considered urban objects. As far as possible, susceptibility relates to all quantities resulting in the frequency F of a hazardous event and, in an even more challenging way, vulnerability V to the consequences C, if the event occurs.

Within the present approach, it is shown that the most specific risk for a single building or infrastructure is

$$R = R\big(u_l(b_k), T_i, D_p, [t_0, t_1], G_h\big), \tag{3}$$

where the following quantities are used:

object type	$u_l(\mathrm{b_k})$	$, k = 1, \dots, n_{urban\ object},$
		$, l = 1, \dots, n_{object\ type},$
threat type	T_i	$, i = 1, \dots, n_{threat,}$
consequence (damage) type	D_p	$, p = 1, \dots, n_{consequence},$
empirical reference time span	$[t_0, t_1],$	
geographic region	G_h	$, h = 1, \dots, n_{geographic\ category}.$

In the following sections of this article, insights of the theoretical framework of [16] are applied and extended. According to Figure 2 the first step includes the definition and the modeling of the urban area. Constructional, geometry and material details for buildings or traffic infrastructure elements are examples for input of the city model. Pre-defined building types are applied to derive information for the consequence assessment [35]. Table 2 in the appendix gives an overview of the applied pre-defined construction types.

Person or traffic densities are further examples of detailed object parameters. Besides the physical and qualitative parameters, regional specifications have also to be classified. As shown in [36], there are differences concerning the frequency of hazardous events and their consequences in dependency on the region.

4 Quantitative susceptibility analysis

In addition to historical event frequency analysis [36], in particular for absolute statistical susceptibility assessments, a scenario information for determination of the local event frequencies is added [16]. This step derives the susceptibility of locations in the urban surrounding to threat events. The basic idea behind the calculation of the quantitative susceptibility is the definition of a local (two-dimensional, (2D), for example. for streets, or three dimensional (3D), for example, within infrastructure, in the following 2D) susceptibility density function, or local event density per time, $f\big(u_l(b_k), T_i, \vec{r}_j\big)$ for every urban object b_k with usage $u_l(b_k)$ and threat type T_i depending on the threat position $\vec{r}_j$. In dependency of the desired discretization resolution, the considered urban surrounding is divided in distinct and compact area elements $A_j, j = 1, \dots, n_{location}$. Every element includes a single possible event location $\vec{r}_j \epsilon A_j$.

By integration over the 2D surface area density, the local absolute event frequency (due to the threats to a single building, per year, for a given region), or local event frequency on area element A_j around the corresponding representative centered event location $\vec{r}_j$ is obtained.

$$F\big(u_l(b_k), T_i, A_j\big) = \oiint_{A_j} f(u_l(b_k), T_i, \vec{r}\,)d\vec{r} \quad , j = 1, \dots, n_{location} \tag{4}$$

The empirical absolute (per building, per time span and for a given geographic area) event frequency $F(u_l(b_k), T_i)$ as achieved from historical event data [36] has to be obtained by summing over all possible event locations,

$$F(u_l(b_k), T_i) = \sum_{j=1}^{n_{location}} F\big(u_l(b_k), T_i, A_j\big). \tag{5}$$

The susceptibility density has to be determined from historical data, physical accesses data and expert estimates.

In particular, the normalization condition (5) has to hold for the selected region. In the following, a modified multivariate Gaussian distribution is used assuming that possible events are concentrated close center of the building for parameterizing the susceptibility density

$$f(u_l(b_k), T_i; \vec{r}) = C_{ik} \cdot F(u_l(b_k), T_i) \cdot \mu(\vec{r}(b_k), L(b_k); \vec{r})$$
$$\mu(\vec{r}(b_k), L(b_k);\ \vec{r}) = 2^{-\frac{\|\vec{r}-\vec{r}(b_k)\|}{\sqrt{L(b_k)}}}. \tag{6}$$

Using equation (4) and (5), one finds for the normalization constants C_{ik}, assuming that all the A_j are sufficiently small and hence the integrations of (4) can be evaluated at $\vec{r}_j$.

$$C_{ik} = \frac{1}{\sum_j A_j \cdot \mu(\vec{r}(b_k), L(b_k); \vec{r})} \tag{7}$$

Considering the influence of all urban objects on the event frequency of threat type T_i at a specific event location $\vec{r}_j$ results in the local cumulated event frequency for a given threat,

$$F(T_i, A_j) = \sum_{k=1}^{n_{urban\ object}} F(u_l(b_k), T_i, A_j). \tag{8}$$

Optional access control, surveillance, social, environmental, economic or other security relevant influences may increase or decrease the empirical threat frequency of building-threat combination. Examples for influences on frequency are the lack of social cohesion or the “broken windows effect” [37]. These effects are not further considered within the scope of this article. The empirical frequency depends only on the historical evaluation in dependency of the region, the object, the building type and the time span considered for historical data evaluation.

The resulting event frequency of equation (8) is in the following applied to define the local absolute quantitative susceptibility S for threat T_i at the event location $\vec{r}_j$ centered within the area element A_j,

$$S(T_i, A_j) = F(T_i, A_j). \tag{9}$$

Using in equation (8), equation (4) and (6), one finds for the Gaussian distribution the local susceptibility

$$S(T_i, A_j) \approx \sum_{k=1}^{n_{urban\ object}} \frac{A_j}{\sum_j A_j \cdot \mu(\vec{r}(b_k), L(b_k); \vec{r})} \cdot F(u_l(b_k), T_i) \cdot \mu(\vec{r}(b_k), L(b_k); \vec{r}). \tag{10}$$

As equation (10) shows, the most basic local susceptibility is defined to be equal to the local event frequency of a given threat type considering the influence of all neighboring buildings.

The summation over all threat types T_i results in the local absolute susceptibility at a specific event location $\vec{r}_j$, centered within the area A_j to all possible threats,

$$S(A_j) = \sum_{i=1}^{n_{threat}} S(T_i, A_j). \tag{11}$$

The summation over all area elements A_j results in the susceptibility to threat type T_i

$$S(T_i) = \sum_{j=1}^{n_{location}} S(T_i, A_j). \tag{12}$$

In equation (11) and (12) , the summation is possibly actually restricted to a subset of threats, if some threats locally do not occur due to a vanishing density according to (4), for example assuming that the event distribution is very localized to the entry of buildings.

A final summation over all event locations $\vec{r}_j$ in the urban region considered leads to the susceptibility of the whole urban environment to all possible threats,

$$S = \sum_{j=1}^{n_{location}} S(A_j) = \sum_{i=1}^{n_{threat}} S(T_i). \tag{13}$$

All frequencies and susceptibilities of equation (4) to (13) have the unit of events (of certain type or set of types) over time. From equation (9) to (13), it also becomes obvious that the susceptibilities are cumulated frequencies.

The introduction of what-if susceptibilities defines the local susceptibility assuming a threat event occurrence. This quantity have the advantage that the absolute threat level must not be determined from empirical data, only the relative distribution of threat types on buildings.

Based on equation (12) , the local what-if susceptibility given a single threat event occurrence is given by

$$\hat{S}(T_i, A_j|T_i) = \frac{S(T_i, A_j)}{S(T_i)} \tag{14}$$

The application of equation (13) results in the local what-if susceptibility for a threat assuming any type of threat has occurred.

$$\hat{S}(T_i, A_j) = \frac{S(T_i, A_j)}{S} \tag{15}$$

The prototype implementation uses a Graphical User Interface (GUI) with 3D visualization of the considered urban area. The presented methodology is exemplarily applied for the evaluation of terroristic threats on a generic urban area. In the following approach, the modeled city is generated with pre-defined building types. An overview of all objects is given in Table 2 and Table 3 in Appendix 1.

The left picture of Figure 3 shows the empirical event frequency for each building according to equation. (5) in dependency of the region. This application example uses historical data of terroristic events from Western Europe of the last 40 years. A detailed overview of the empirical data is published in [36] . Table 3 in the appendix gives the empirical values for the frequency and the consequences of all the numbered objects in the left picture of Figure 3. The empirical approach allows a fast assessment of the considered urban area and critical elements are easily identified in dependency of the object type and the region. The empirical event frequencies in the left picture of Figure 3 show the criticality of single urban items, but the interaction with neighbored objects and possible applications of countermeasures are not considered. The defined quantitative susceptibility approach cures the weak points of the pure empirical assessment.

Based on the applied historical data, the embassy (building no. 9) has a relative high empirical frequency, as shown in the left picture of Figure 3. As an indicator for an industrial society, objects with the usage of a corporation (building no. 1), finance and trading (building no. 2 and 3), and small and medium enterprises (building no. 6) have high to medium values concerning the number of events per year and building.

For direct comparison with the left picture of Figure 3, it would be most appropriate to plot the local susceptibility for all types of threats $S(A_j)$ according to equation (11). Using the what-if susceptibility $\hat{S}(T_i, A_j)$ according to equation (15) assuming that a threat event has taken place, is believed to be even more instructive, see the right picture of Figure 3.

Maximum values indicate positions with expected highest susceptibility. For each possible event location, the influence of all urban objects and their corresponding event frequencies is considered, distributed around the buildings using equation. (6). In particular between buildings 9 and 10 neighboring effects are nicely visible. This building front is now assessed to be more susceptible than any front of building 1, which was the second susceptible building within the pure empirical approach. In summary, the visualized results give the information on which possible event location has the highest expected susceptibility, if an event occurs. In the context of resilience management, this information can be used to prevent events.

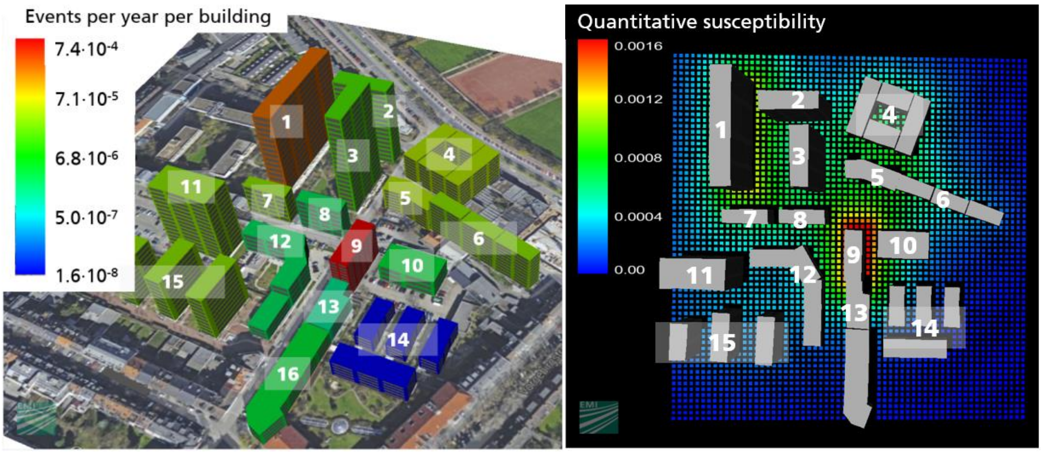

Figure 3: Left: Empirical frequency of all types of terroristic events in dependency of the region and the building or infrastructure (absolute annual susceptibility) Right: Visualization of local threat frequencies of all types of terroristic events in an urban surrounding using an areal density function assuming an event takes place (what-if susceptibility). The quantitative susceptibility indicates the probability of occurrence for a hazardous event on a specific local area. The results are based on historical data of Western European countries for the last 40 years.

5 Consequence analysis

According to Figure 2, the next step after the susceptibility calculations includes the evaluation of vulnerabilities in terms of consequences (damage effects) using physical and deterministic models. The expected losses caused by a threat T_i are calculated by using a physical hazard (propagation) model $H(T_i, \vec{r}_j; P)$ in dependency of the threat type T_i and the event location $\vec{r}_j$. The attribute P describes the physical parameters that are computed to describe the (time dependent) hazard potential. In this notion, H covers all the potentially hazardous physical effects of the threat. Examples for the physics can be the magnitude of an earthquake or the characteristic blast sizes of an explosive event.

The consequences C (damage effects) of type D_p at position $\vec{r}_o$ in the result grid, caused by the threat T_i at location $\vec{r}_j$ in the grid of the urban environment, are defined for a specific hazard model H as

$$C\left(H(T_i, \vec{r}_j; P), \vec{r}_o, D_p\right). \quad (16)$$

The consequences in equation (16) are local individual damage effects per person or object with respect to the given damage type in case of occurrence of the threatening event. A single hazardous event may have multiple types of consequences.

5.1 Physical and engineering models for consequences

Following equation (16), the physical assessment of consequences of type D_p 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 [24], three main categories of consequence types are evaluated:

1. damage (injuries or fatalities) inside or outside of a building,
2. Structural damage of buildings or infrastructure elements and
3. Monetary damage of buildings or infrastructure elements.

A further differentiation of monetary damage are direct or indirect costs after a hazardous event. The consequences and hence the vulnerability can be categorized into direct/ indirect and tangible/ intangible consequences and vulnerability, respectively [38]. Structural damage on a building is characterized as direct and tangible vulnerability, for example. There are existing models to cover indirect economic consequences, for example the Input-Output model of Haimes [39]. The vulnerability of urban areas related to indirect losses depends on many different indicators [32] and indirect losses are not further investigated in this article.

The presented approach is exemplarily applied for the evaluation of terroristic threats. A detailed historical analysis concerning the tactics of such incidents has shown that explosive events are the scenarios with the highest risk. They are associated with the highest frequency of occurrence and the most severe consequences [36]. An explosion releases a large amount of energy which propagates in form of a blast wave. Combustion products, fragments and debris are neglected within the scope of this work and hence the response purely to the blast wave is investigated. According to equation (16), Table 1 gives an overview of parameters employed in hazard models for the evaluation of consequences due to blast loading.

Table 1: Specification of a hazard model for description of blast loading effects.

Parameter	**Description**	**Parameter for specification**	
T_i	Threat	Charge weight class	W
$\vec{r}_j$	Event location	Position in the urban area	
P	Physics	Peak overpressure	p_{so}
		Blast impulse	I_o

The local blast parameters p_{so} and I_o depend on the charge weight W, its position $\vec{r}_j$ and the urban geometry. There are different techniques for parameter estimation. A common semi-empirical method has been proposed by Kingery and Bulmash using a ninth-order compound polynomial equation [40]. This methodology is valid for free field blast waves and depends only on the distance between the event location and the position in the result grid $|\vec{r}_j - \vec{r}_o|$. Klomfass, et al. [41] published a more detailed approach for densely built urban areas. This Computational Fluid Dynamics (CFD) tool is based on a finite volume approach and allows the consideration of focusing and shading effects, which occur if an air shock wave propagates among buildings [42]. The present methodology weights the vulnerability over multiple threats and positions, which has a strong effect on the calculation effort. Therefore, the subsequent assessment uses the fast and efficient approach from Kingery and Bulmash [40] and the complex shock wave propagation in a build environment is neglected.

Besides the physical description of the hazard, a further essential step includes the availability of consequence models. The derived blast loading parameter allows an estimation of injuries in open space and in buildings using different models. Lethality estimation in dependency of the derived blast loading parameter for persons outside of buildings can be made with the empirical model of Bowen et al. [43]. Axelsson and Yelverton [44] give a further assessment scheme with the use of a physical single degree of freedom model (SDOF) to predict lung damage of humans exposed to blast. Based on the evaluation of observed losses after the V2 bombing attacks in London (Second World War), a model for injury prediction in buildings was proposed by Gilbert, et al. [45]. They use statistics as basis for this model including number of unaffected, slightly, seriously and fatally injured persons in buildings in dependency of identified distance areas to the missile impact. With the model of Gilbert, et al. a combined consequence assessment of blast, fragments and debris is considered. Based on the historical data in the model of Gilbert [45], the criteria apply the housing of that period and should be interpreted as a first indication.

To predict the structural response due to blast loading, single degree of freedom (SDOF) models are common practice [46], [47]. Pressure-impulse diagrams are an extension of these models and provide a design chart for failure behavior of an arbitrary blast loading scenario [48], [49]. Applications can be found for different materials and structural members for example masonry [50], reinforced concrete [51], glass [52] or façade elements [53].

The application of the SDOF method delivers the initial damage of single 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 different building types in accordance with the construction information [35]. Selected and applied building types are shown in the appendix in Table 2. In this publication, the known methods of direct design and alternative load path are combined in one holistic procedure. The results are implemented in the software demonstrator. The application of these 10 different building types allows an approximation of arbitrary urban areas.

The presented assessment scheme is independent of the used physical models. According to equation (16), the already implemented models of the software demonstrator are applied. In summary, the following empirical, physical and engineering models are used:

- empirical assessment of injury due to blast loading [43],
- probit curves for the effects on people in buildings [45],
- single degree of freedom models for structural damage to wall sections, columns and windows [48], [54],
- engineering approach for progressive collapse behavior of buildings, using initial structural damage and alternative load path method [35].

5.2 Example application of the consequence models

The following first example in consequence quantification considers a single event at a single position in front of a building. Based on the empirical frequency assessment and the susceptibility analysis in Figure 3, building no. 9 of the urban environment is chosen for evaluation. With the assumption, a single type of hazard event happens and in case of a single threat, the evaluation of a single object the susceptibility of equation (13) is equal to one.

$$S = S(T_i, A_j)\,, \qquad k = i = j = 1 = n_{object} = n_{threat} = n_{location} \tag{17}$$

The calculated blast impulse and peak overpressure in dependency of the position on the building façade build the basis of the hazard model H of equation (16). In Figure 4, the hazard of a vehicle (car, transporter, truck) bomb (Vehicle Borne Improvised Explosive Device, VBIED) scenario in front of a building is evaluated. Similar to the evaluation grid on the urban surface introduced along with equation (1), the building surface is separated into different surface areas for each floor. The semi-empirical approach of Kingery and Bulmash [40] provides for a single segment the physics of the hazard using the explosive quantity and the distance to the threat. The angle between the line of sight and the normal vector of the segment area is used additionally, to determine the pressure increase due to reflection [55]. As expected, Figure 4 shows a decreasing intensity of the hazard parameters with an increasing distance to the threat location.

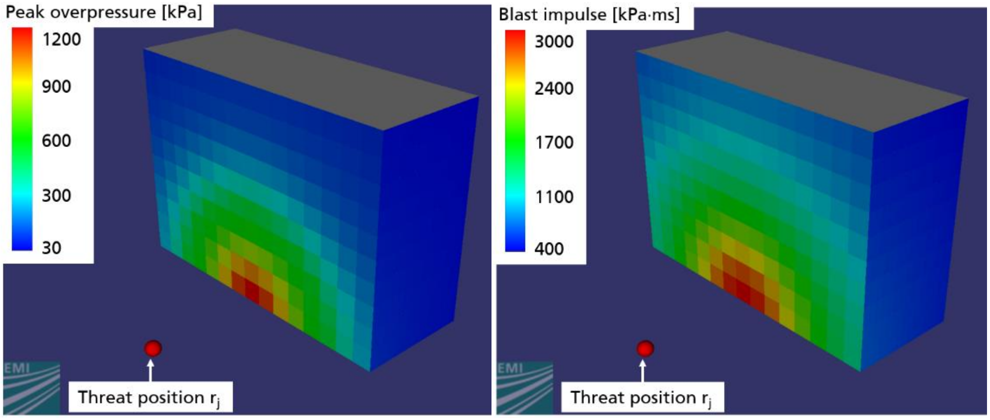

Figure 4: Evaluation of a single explosive vehicle bomb scenario in front of a building. The physical hazard parameters of the hazard model H are the peak overpressure (left) and impulse (right) in dependency of the position on the building façade.

The derived hazard model H of Figure 4 is applied to calculate the resulting consequences (damage) for the given threat scenario in form of a car bomb event. Besides the position and the dimension of an urban object, a number of further parameters are used to assess the consequences. In the applied example, the single building is modeled as 10 story office building with a reinforced concrete frame construction, as shown in the left picture of Figure 5. The façade uses window elements with toughened glass. For the office use, a typical density of 0.011 persons per square meter is assumed for evaluation.

Based on the hazard analysis of Figure 4, the initial damage of load bearing elements is calculated, see the right picture of Figure 5. In this diagram, the peak hazard values for each floor are applied to evaluate the damage state of the reinforced concrete columns using a single degree of freedom model. This is a floor-wise worst case approach for damage assessment.

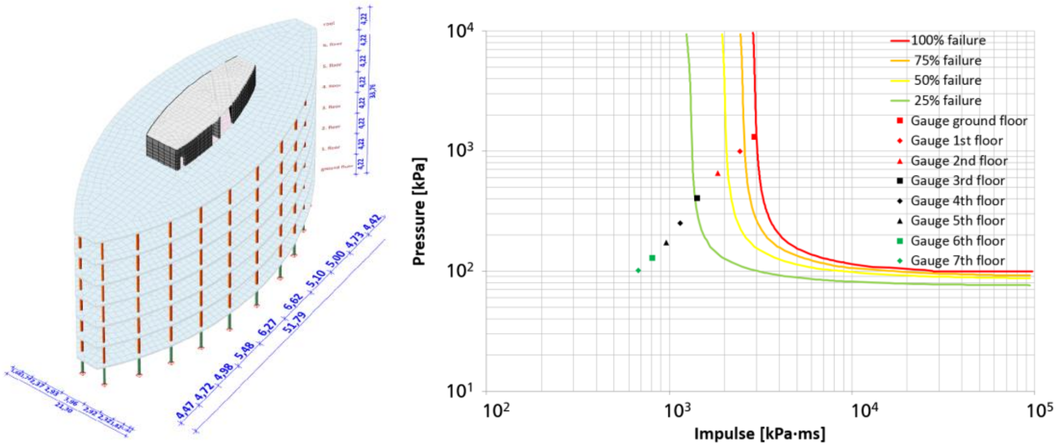

Figure 5: Detailed model of an office building (left) [35] and the initial damage assessment of load bearing reinforced concrete columns (right). The iso-damage curves are calculated with a single-degree of freedom model and give the information on the failure state of each structural member for a given loading.

The consequences for a single scenario ($n_{location} = n_{threat} = 1$) in front of the building according to equation (16) are shown in Figure 6. Due to the assumption that the event takes place, the result can be interpreted as a conditional (consequence, damage) probability. Alternatively it can be interpreted as what-if risk assuming the susceptibility of equation (17), or as what-if vulnerability as introduced below.

Based on the initial damage assessment of Figure 5, the resulting progressive collapse is predictable as proposed by Müllers et al. [35]. The right picture of Figure 6 shows the resulting structural damage to the building. All window elements will break and the predicted initial damage of load bearing elements will cause a progressive collapse with probably 50%.

The left picture of Figure 6 shows the estimated injury probability to people inside and outside the building based on [43] and [45]. A closer distance to the threat position will cause a higher criticality for people outside the building. The visualized result for persons inside the building is averaged over all floors. The applied consequence model predicts a rate of 14% of critically affected persons inside the building by the considered scenario.

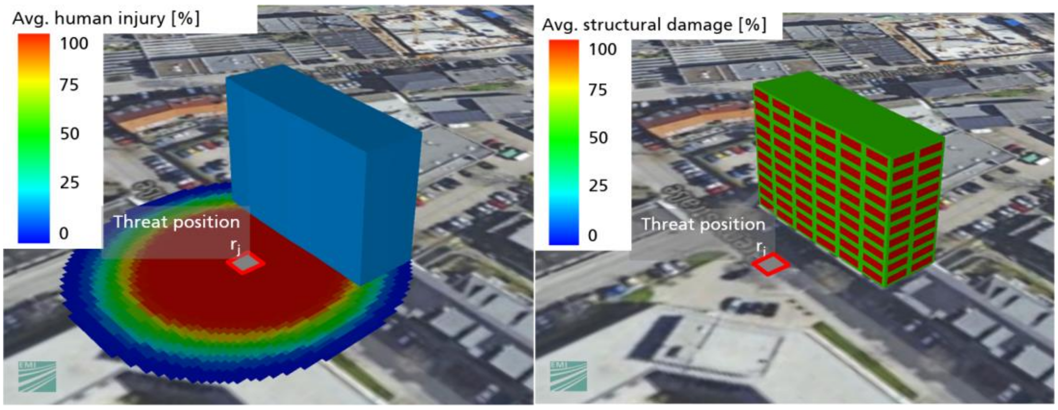

Figure 6: Consequence estimation for a single explosive hazard source at a single position for a single building. Left: Predicted lethality inside and outside of the building (averaged). Right: structural damage for toughened glazing elements of the façade and the load bearing columns response of the building.

5.3 Validation of the engineering models

A back calculation of a terrorist event is carried out for validation of the presented consequence approach. The Oslo bombing on 22 July 2011 is chosen for comparison of consequences.

A car bomb was parked in front of the Office of the Prime Minister of Norway. The detonation caused 8 fatalities and 209 injuries. There was window damage recorded up to 400 meters distance. Detailed information about the window damage can be seen in the right picture of Figure 7 [56]. No serious damage concerning load-bearing components occurred due to the strong and monolithic constructions. A back calculation from Christensen and Hjørt [56] estimated the charge weight of the car bomb, which is used to derive the model consequences.

The surrounding neighborhood of the Prime Minister's office is modeled as basis for validation. The pre-defined construction types approximate the urban objects of the considered city quarter. Mainly office buildings or office towers are considered with a reinforced concrete framing construction. Empirical person densities are included to estimate the number of people inside the building, again 0.011 persons per square meter for a building with office use are employed.

The approach predicts 161 casualties in buildings, which compares well to the 217 observed casualties after the hazardous event. The result can be evaluated better if it is assumed that also people outside buildings were among the casualties. The presented approach did not predict any progressive collapse, which is consistent with the real scenario.

Finally, a comparison of the glazing damage is shown in Figure 7. The consequence assessment slightly overestimates the glazing damage and delivers a conservative prediction. During the interaction of a shock wave with a building façade, there are different effects, which will decrease the intensity of the hazard potential. Lightweight elements like windows fracture and the blast enter buildings. Architectural features of the façade are further essential properties, which can decrease the intensity of the explosion event [52]. The applied approach for physical quantification of the blast event assumes buildings with perfectly rigid reflecting surfaces, which overestimates the intensity of the shock wave and results in conservative predictions of the consequences.

In summary, the calculation of personal and structural damage reveals sufficient accuracy for extended vulnerability and risk predictions when using in the following multiple events.

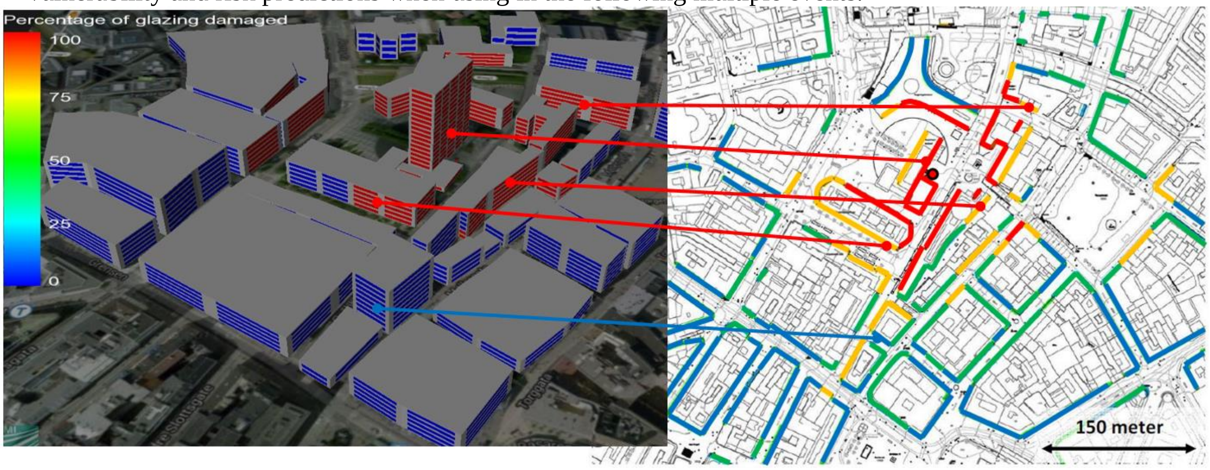

Figure 7: Back calculation of the Oslo bombing on July 22nd in 2011 with the presented physical consequence approach. Comparison of the damage estimation for a single event (left) with the recorded glazing damage after the terrorist attack (right) according to [56].

6 Vulnerability and risk assessment

6.1 Consideration of multiple possible event locations

The physical consequence results, as shown in Figure 6, are conditional local probability values and give an answer to the question "what happens if a single scenario takes place?" The presented results in Figure 6 are similar to well established approaches like the RAMCAP approach [21] or the reference manual FEMA-426 [22] discussed in section 1.2. These schemes are based on a hazard analysis to define single decisive scenario and critical infrastructure elements for a subsequent derivation of threats, vulnerabilities and risks. The present methodology defines vulnerability differently, as consequences (damage) in case of events.

This approach overcomes the difficult challenge of the prediction of a decisive event location and intensity. Effects on neighboring objects can be considered. To do so, the introduced assessment scheme will weight the expected losses over different threat positions and intensities. This will initially be performed without using empirical-analytical information. Stepwise, as empirical and expert information is added, this will lead to an averaging risk analysis considering multiple threat types and hazard source positions.

The introduced consequence model of equation (16) is used to define the "what-if" vulnerability, see equation (18).

$$V\left(H\left(T_i, \vec{r}_j; P\right), \vec{r}_o, D_p\right) = C\left(H\left(T_i, \vec{r}_j; P\right), \vec{r}_o, D_p\right) \tag{18}$$

Assuming that the local distribution of a single threat type is completely unknown (homogeneous distribution), the vulnerability is averaged over multiple positions of the threat. The local vulnerability at position $\vec{r}_o$ of the surface evaluation grid for consequence type D_p in case of an event of threat type T_i is averaged over all possible event locations $\vec{r}_j \in A_j$

$$V_{hom}\left(H(T_i; P), \vec{r}_o, D_p\right) = \frac{1}{n_{location} \sum_j A_j} \sum_{j=1}^{n_{location}} A_j \cdot V\left(H\left(T_i, \vec{r}_j; P\right), \vec{r}_o, D_p\right) \tag{19}$$

Equation (19) uses equation (18) to define the local resolved what-if vulnerability without any empirical input on the event distribution. It quantifies the vulnerability at a specified position in the urban area with respect to a certain type of consequences, caused by a given hazard without any limit on the event location. In particular, the expert estimate that the events are concentrated close to the building is dropped. Therefore, equation (20) defines a homogeneous what if susceptibility given all threat types and intensities T_i,

$$\hat{S}_{hom}\left(T_i, A_j | T_i\right) = \frac{A_j}{n_{location} \sum_j A_j} \tag{20}$$

Extending the vulnerability assessment of Figure 6, the computation of (19) includes the consideration of different event locations. According to the application example of section 5.2, the car bomb scenario would be placed at different locations in front of the building, for each of which, assuming a regular rectangular event grid, the same probability would be assumed. It is natural to go a step beyond this homogeneus susceptibility assumption of equation (20).

Using equation (14), the what-if susceptibility $\hat{S}\left(T_i, A_j \middle| T_i\right)$ is calculated for each possible location on the road in front of the building. Figure 8 presents the susceptibility of different threat positions for a single threat type and intensity. It is assumed that the local distributions are equal for every threat type and intensity. The threat positions are distributed over two lanes along the street in front of the building. The first lane is placed 10 m away from the building taking account of physical access control. The distance between two points is 5 m in each direction.

The event occurrence is distributed using the local susceptibility density of equation (14) with equation (10) and results for a single building in

$$\hat{S}\left(T_i, A_j | T_i\right) = \frac{A_j \cdot \mu\left(\vec{r}(b_k), L(b_k); \vec{r}_j\right)}{\sum_j A_j \cdot \mu\left(\vec{r}(b_k), L(b_k); \vec{r}_j\right)}, \qquad k = 1 \tag{21}$$

Modulo normalization, equation (21) is a function of the building dimension and the distance of the event locations to the building. Possible locations with a closer distance to the urban object have a higher frequency of occurrence when using the susceptibility density function of equation (6). The bar diagram in Figure 8 shows the marginal distribution (sum of the two event probabilities below the bar) of the discrete density function to assess the susceptibility at different positions in case of a single threat type and threat intensity.

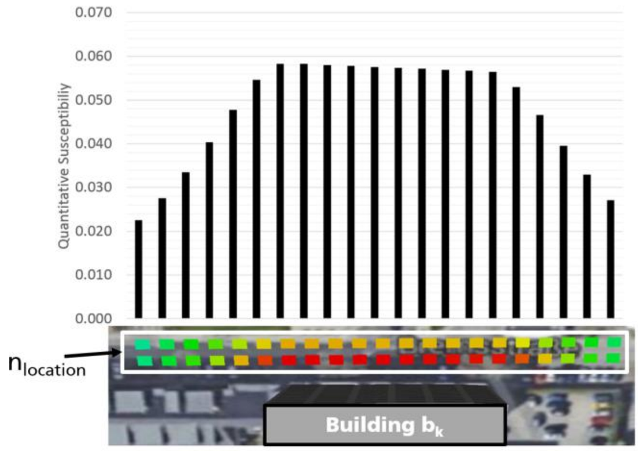

Figure 8: Normalized quantitative what-if susceptibility in front of a building to evaluate the probability of occurrence, if an event of a certain threat type and intensity takes place. The application of the density function assumes a higher probability with closer distance to the considered urban building object. In the present case, according to the city plan, the road has a

little more distance to the building at the right hand side, resulting in the minor decrease of the event probabilities at the right hand side in front of the building.

The combination of the vulnerabilities of equation (18) for each event position and the local what-if susceptibility for a single threat type and intensity of (14), here using the sample approximation of equation (21), results per definition in a what-if susceptibility weighted vulnerability

$$V\big(H(T_i;P);\vec{r}_o,D_p\big) = \sum_{j=1}^{n_{location}} \hat{S}\big(T_i,A_j\big|T_i\big)\cdot V\big(H\big(T_i,\vec{r}_j;P\big);\vec{r}_o,D_p\big)\ ,\ \ i=k=1 \tag{22}$$

In equation (22), every possible event location $\vec{r}_j$ will cause an independent vulnerability of type D_p at position $\vec{r}_o$ and is weighted with the corresponding what-if susceptibility at each event position assuming the selected hazard type and intensity occurrence. In the used notation in equation (22), the what-if susceptibility takes account of the effect of all buildings. In the present sample case, when using equation (14) of course only the susceptibility of a single building is entering. It is important to observe, that the what-if vulnerability of (22) for a single threat type and intensity is independent of empirical event frequencies. However, it depends on the shape of the susceptibility density distribution, which is based on expert assumptions informed by past event locations.

For the application example, the result for a single threat type and intensity ($n_{threat} = 1$) at different locations ($n_{location} = 42$) is shown in Figure 9. In comparison with the vulnerability for a single event location of Figure 6, the what-if susceptibility weighted vulnerability for a single threat type and intensity can have lower values. In the present case, due to possible positions with lower probability of occurrence or longer distances to the building object at risk, the averaged vulnerability value for the estimated progressive collapse in Figure 9 is only 22%. Still a failure of all window elements expected. This result can be interpreted that in 22% of all relevant attack events with explosives of the selected type and intensity the load bearing structure will at least be partly destroyed. In this case, on average the most remote windows are affected least, see the upper right corner of the building in Figure 9. This modified assessment of the vulnerability of the building due to the selected threat type and intensity originates from the simultaneous consideration of multiple different event positions.

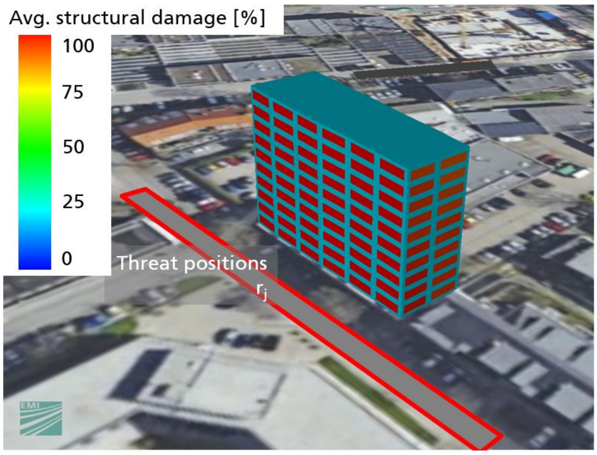

Figure 9: Averaged vulnerability for a single threat type and intensity using a local what-if susceptibility for 42 event locations that prefers event locations close to the building. Color coding of the predicted structural damage for glazing elements (ca. 80% to 100%) of the façade and of the load bearing structure of the building (ca. 25 %).

6.2 Consideration of multiple possible threats

The foregoing vulnerably approach in equation (22) assumes that a single threat type and intensity take place at different positions and do not make any assumptions about the frequency of threat types and intensities. Only the local event frequency was assumed to concentrate around building objects. For urban objects, it can be computed without any empirical input on frequencies.

The occurrence of different explosive events with varying net explosive quantities is assumed. Similar to equation. (19), the simplest approach is to assume that all threat types are equally likely. In this case, only the definition and number of threat types allow expert input based on past events. Based on equation (19), the vulnerability at a specific location in the urban environment averaged over all threat types is obtained, assuming that threat events are homogeneously distributed with respect to the threat categories,

$$V_{hom}(\vec{r}_o, D_p) = \frac{1}{n_{threat}} \sum_{i=1}^{n_{threat}} V_{hom}(H(T_i; P), \vec{r}_o, D_p). \tag{23}$$

Besides the urban geometry constraints, equation (23) is able to consider different threat types with different intensities. Related to the threat of terroristic explosion events a varying intensity is considered using different charge weights. The summation in equation (23) is possible only for threats, which lead to the same type of consequences D_p, for example injury of persons.

Similar to (14) and (20), a homogeneous what-if susceptibility for all threat types can be derived by inserting (22) into (23).

$$\hat{S}_{hom}(T_i, A_j) = \frac{A_j}{n_{location} \cdot n_{threat} \sum_j A_j} \tag{24}$$

The foregoing examples with single (Figure 6) and multiple (Figure 9) event locations used a given single charge weight in the range of a medium vehicle bomb to evaluate a terroristic explosive event. Going beyond the foregoing examples, the further vulnerability computation investigates the behavior in case of multiple threat types and intensities taking in addition their relative frequency into account. This also goes beyond (24), which assumes a homogeneous distribution of events. Besides the medium VBIED scenario, small and large suitcase bombs, small, medium and large car bombs are considered. Hence, at a single event location five scenarios with different intensities are considered.

With insights from empirical data of terroristic explosive events [36] it is assumed, that events with a smaller charge weight have a higher probability of occurrence [57]. In a similar manner, the local what if-susceptibility assuming a threat out of a set of threats occurs according to equation (15) results with the subsequent use of equation (13) and (10) in

$$\hat{S}(T_i, A_j) \approx \frac{1}{\sum_i \sum_k F(u_l(b_k), T_i)} \sum_{k=1}^{n_{urban\ objects}} \frac{A_j \cdot F(u_l(b_k), T_i) \cdot \mu(\vec{r}(b_k), L(b_k);\ \vec{r}_j)}{\sum_j A_j \cdot \mu(\vec{r}(b_k), L(b_k);\ \vec{r}_j)} \tag{25}$$

For a single urban object at risk $n_{urban\ object} = 1 = k$, equation (25) reduces to

$$\hat{S}(T_i, A_j) \approx \frac{1}{\sum_j A_j \cdot \mu(\vec{r}(b_k), L(b_k);\ \vec{r}_j) \cdot \sum_i F(u_l(b_k), T_i)} \cdot \mu(\vec{r}(b_k), L(b_k);\ \vec{r}_j) \tag{26}$$

Equations (20) and (26)only differ by the second factor, which is the empirical ratio (percentage) of the threats for the given urban object type. In the case of multiple urban objects as in equation (25), the expression is more complex. However, in both cases it can be shown, that the absolute threat frequencies are not needed for the computation of the threat-frequency weighted what-if susceptibilities of (25) and (26).

When inspecting equation (25) , and in a more straightforward way (26), it becomes obvious that for computing these expression it suffices to use the relative threat distribution ratio σ.

$$\sigma(u_l(b_k), T_i) = \frac{F(u_l(b_k), T_i)}{\sum_i F(u_l(b_k), T_i)} \tag{27}$$

The application of equation (27) in equation (25) results in

$$\hat{S}(T_i, A_j) \approx \frac{1}{\sum_i \sum_k \sigma(u_l(b_k), T_i)} \sum_{k=1}^{n_{urban\ objects}} \frac{A_j \cdot \sigma(u_l(b_k), T_i) \cdot \mu(\vec{r}(b_k), L(b_k);\ \vec{r}_j)}{\sum_j A_j \cdot \mu(\vec{r}(b_k), L(b_k);\ \vec{r}_j)} \tag{28}$$

The threat frequency and local distribution weighted what-if vulnerability is defined as

$$\mathrm{V}(\vec{r}_o, D_p) = \sum_{i=1}^{n_{threat}} \sum_{j=1}^{n_{location}} \hat{S}(T_i, A_j) \cdot V(H(T_i, \vec{r}_j; P), \vec{r}_o, D_p), \tag{29}$$

where the local frequency-weighted what-if susceptibilities for multiple threats according to equation. (15) are used.

For a sample application, Figure 10 shows the quantitative susceptibility for each possible position in dependence of the distance to the object and the threat type according to equation (26). The susceptibility at a given position is differentiated for all threat intensities by using the weighting factors of equation (27). The pie chart in Figure 10 visualizes the distribution of different threat types according to the second factor of (25). The bar chart shows the marginal distribution by summing up the susceptibilities of the two event locations depicted below according to (25), that is the total susceptibility sums up to unity as defined in section 4.

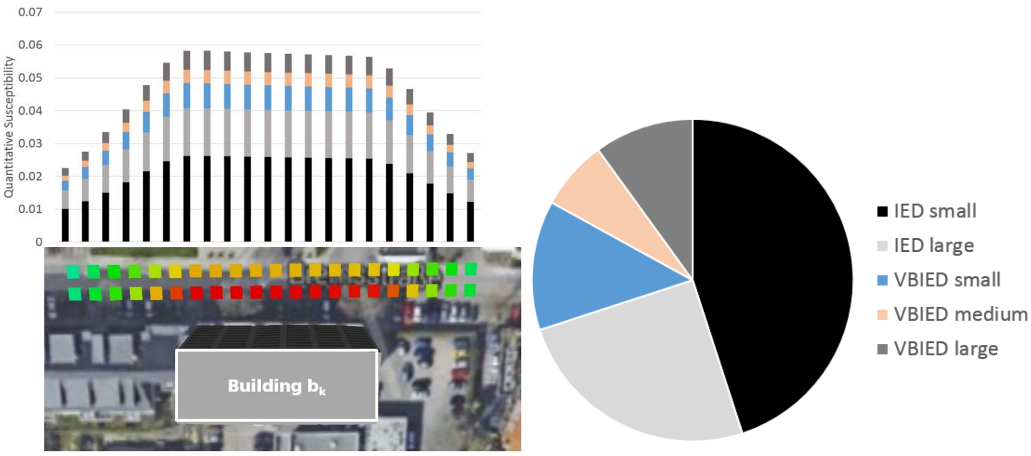

Figure 10: Normalized what-if susceptibility in front of a building (left picture) taking into account the empirical distribution of threats and a local distribution assumption for each event location and threat type. The density function assumes a higher probability closer to the urban object. The bar chart show the marginal susceptibilities for the two event locations depicted below, respectively. The identical threat ratio distribution assumed at all given positions is visualized in the pie chart on the right side.

For the application example, the local what-if vulnerability at the building surface is calculated according to equation (29). Figure 11 shows that the overall what-if vulnerability for progressive collapse is 17%. Due to the higher susceptibility of threat types with lower intensity, the weighted result is slightly smaller in comparison with the foregoing example with a single threat intensity (Figure 9), which resulted in 25 %. This difference becomes even more obvious when considering the effects on the glass windows.

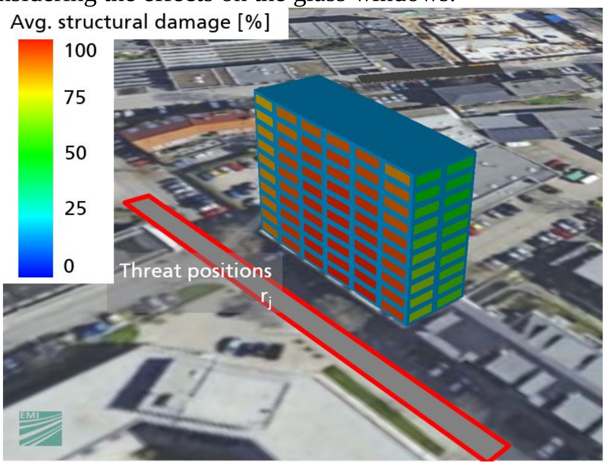

Figure 11: What-if vulnerability for multiple threats ($n_{threat} = 5$) at different possible locations ($n_{location} = 42$). Predicted structural damage for glazing elements of the façade and the load bearing response of the building. The possible event location are within the red rectangle.

The defined vulnerabilities in equations (18), (19), (23) and (29) take into account of the fact that the vulnerability depends on the threat types considered as well as their location. Nevertheless the definitions try to avoid as far as possible to use empirical input.

As discussed already, the what-if vulnerability according to equation (29) takes into account a number of empirical inputs: assumptions on the local distribution in the vicinity of urban objects, the definition of threat type classes and the ratio of the threat intensities. In this sense, already equation (29) could be addressed as what-if risk in case of a threat event of unknown type.

In the present approach, only the following quantity is categorized as a risk quantity, since it uses the absolute event frequency for threat events, assumptions on threat classes as well as assumptions on the event distribution around buildings. Using the absolute susceptibility of equation (9), the local annual risk due to all kinds of threats is defined as

$$R(\vec{r}_o, D_p) = \sum_{i=1}^{n_{threat}} \sum_{j=1}^{n_{location}} S(T_i, A_j) \cdot V(H(T_i, \vec{r}_j; P), \vec{r}_o, D_p), \tag{30}$$

The defined approach offers a detailed susceptibility, vulnerability and risk quantification with consideration of explicitly controlled historical-empirical data input. In alignment with the considered historical data, the methodology does not determine the worst case scenario, but allows to determine the average expected susceptibility, vulnerability assuming an event occurrence and averaged risk. The strength of this scheme is delivered by the statistical assessment of multiple weighted threats at multiple locations in combination with physical engineering models to derive the expected consequences.

6.3 Multiple objects, threats and event locations in a city quarter

The physical risk and vulnerability approach is finally applied to a complete urban environment. In this case in addition multiple urban objects are considered for the evaluation of equation (29), that is, the restriction used in the examples above to $n_{uo} = 1$ is resolved. It assumes that one threat out of the threat type set defined above takes place.

The local what-if vulnerability for each urban object is computed with equation (29), assuming the what-if susceptibility distribution defined in (15). The left picture of Figure 12 shows the vulnerability of glazing and façade damage and the right picture of Figure 12 shows the progressive collapse. The results visualize the expected loss if one threat occurs, weighted over all possible event locations, threat intensities, considering the threat due all buildings, in alignment with their location, dimension and orientation. This quantitative assessment allows a precise estimation of the what-if vulnerability.

The most vulnerable elements or weak spots of the urban environment are easily detected to support decision makers. The comprehensive investigation reveals vulnerable elements of the urban area. By using the density distribution function of possible event locations, the interaction of urban objects is evaluated, that is, the neighboring effect is taken into account.

Due to the addition of multiple products of what-if susceptibility and vulnerability in (29), the vulnerability results visualized in Figure 12 can be translated into risk values. The absolute susceptibility analysis of Figure 3 resulted in event frequencies between 10^{-8} to 10^{-4} events per year and object. This is used within (29) to compute the annual local risks, which reflects in the final result.

Based on the consideration of the whole urban area in case of an event, the office building (no. 9 in Figure 12), will experience with 4-5% probability a progressive collapse. Taking the absolute susceptibilities per building object of Figure 3 into account, the total event frequency can be computed be of the order $3.8 \cdot 10^{-5}$. Hence, the absolute probability for building collapse is of the order of $1.9 \cdot 10^{-6}$ per year.

Due to the interaction with neighbored objects, there are buildings that have low values concerning the susceptibility but show critical vulnerability and risk results (objects no. 5, 8 and 10), see left picture of Figure 3 and Figure 12. This even holds true when comparing with the local what-if susceptibility of the right picture of Figure 3. Hence equations (29) or (30) are most suitable for summarizing information relevant for decision making.

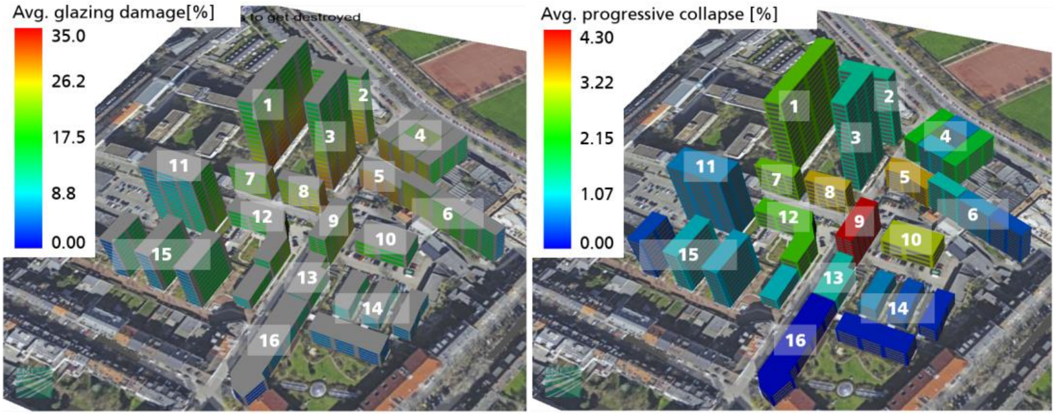

Figure 12: What-if risk estimation for an urban environment assuming 5 threat types, 3052 possible event locations for each threat types around 27 urban objects. Expected loss estimation in case of an event for façade and glazing elements (left) and for progressive collapse (right): probability of damage in case of an event.

7 Measures to reduce vulnerability and enhance resilience

Existing risk assessment schemes encourage the further step of risk mitigation, based on the risk computation and evaluation [21], [22]. According to Figure 2, resilience enhancement measures can be applied, if the calculated susceptibilities, vulnerabilities and/or risks are not acceptable.

A relative risk reduction ΔR is proposed in equation (31) to quantify the effectiveness of the applied enhancement measure. Per definition, the risk based values are nonzero and always positive. Hence, the difference of the vulnerability of equation (29) or the risk of equation (30) before and after the application of security measures can be related to the initial vulnerability or risk. This allows computation of the relative risk reduction

$$\Delta R = \frac{R^{initial}\left(\vec{r}_o, D_p\right) - R^{enhanced}\left(\vec{r}_o, D_p\right)}{R^{initial}\left(\vec{r}_o, D_p\right)}. \tag{31}$$

The relative risk reduction ΔR is positive if the urban scenario improves after the intended enhancement measures and negative if it worsens.

For further assessment, the derived value of equation (31) can be used in decision-making processes to quantify the benefit of a certain enhancement measure. Oriented to Mueller and Stewart [58] or Stewart [23], the result of equation (31) can build the initial value for cost-benefit assessments.

Based on the calculated results in Figure 12, two different options are exemplarily applied to increase the robustness of the considered urban environment and a comparison is given in Figure 13. According to equation (30), the risk of all critical objects is summarized. The first security measure consists of roadblocks to decrease the probability of terroristic events using larger amount of explosives close to buildings. With respect to the introduced resilience phases in section 1, this measure contributes to the resilience management phases "preparation" and "prevention" and decreases the susceptibility close to the building and hence an improved overall urban scenario emerges. According to equation (31) and all objects of the application example, the installation of a roadblock results in a reduction of 97%.

The generation of stand-off distances changes the susceptibilities and this enhancement measures results in relatively low risk values. This kind of mitigation measure is not applicable for every situation. The lack of room, socio-political aspects, and the blocking of emergency and escape routes are valid arguments against the application of such enhancement measures. Of course, the present example did also not take into account that the event locations might shift to other urban quarters.

A further enhancement measure consists of reinforcing the load bearing elements of selected buildings. This addresses the resilience management phase "protection". In the considered example, a retrofitting with an innovative high-performance concrete [59] is applied for objects with an initial what-if vulnerability greater than 3%. Besides the embassy (building no. 9), the buildings 5, 8, 10, and 12 are retrofitted. This measure increases the robustness and decrease the vulnerability without changing the susceptibility. The right picture of Figure 13 shows the resulting averaged what-if vulnerability according to equation (29). Black framed objects are retrofitted with the high-performance concrete. In comparison with the right picture of Figure 12 and applying equation (31), this measure results in a summarized damage reduction of 92% concerning progressive collapse for the enhanced objects.

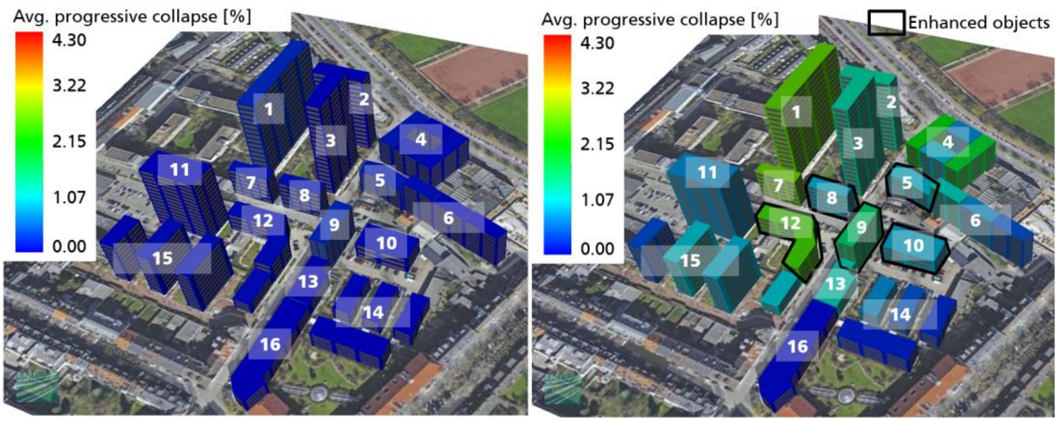

Figure 13: Comparison of what-if vulnerabilities after the application of different resilience enhancement measures. Realization of a road block (left) and the enhancement of load bearing members for selected urban objects.

With the presented approach, the effectiveness of security measures can be illustrated in a quantitative manner using the relative risk reduction of equation (31). The example compared two different enhancement measures to minimize the overall risk of the urban quarter. In the presented application example, mitigation measures for susceptibility reduction result in (locally) slightly better results than measures of vulnerability reduction. For other threats this effect is seen to be even much more dominant, for example when preventing the access of almost all larger explosive threats (e.g. truck bombs). Social and economic impacts of different security measures have to be considered, if they are applied for a given urban situation. A roadblock can (locally) significantly reduce the impact of possible attack events, but could also have influence on the accessibility to single objects or emergency escape routes, besides triggering the above mentioned relocation effect.

8 Conclusions

This article proposes an extended formulation for risk assessment of whole urban areas. The approach allows to define unambiguously susceptibility in terms of frequency, probability and exposure quantities. Vulnerability is defined in terms of hazard and damage quantities. Several types of susceptibilities and vulnerabilities are defined that allow to incorporate stepwise information, as available in urban planning, enhancement and change processes. The concept combines these quantities to averaged risk quantities.

To overcome possibly weak and limited reliability of empirical consequence data an conception with physical and engineering models is introduced to improve the assessment of susceptibilities, vulnerabilities and risks. The comprehensive risk assessment and management scheme is divided into four main parts and includes the scenario definition, the susceptibility assessment, the vulnerability and risk evaluation and finally the optional application of resilience enhancement measures. It is shown how this strongly supports activities within a number of resilience management steps, namely preparation, prevention, protection and response.

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 of threat events in dependency of the region and the urban object type. A quantitative and local susceptibility analysis scheme is introduced to combine empirical data with an arbitrary urban environment by taking account of geometrical constraints and by assuming event localization close to buildings. Besides using the empirical data, the susceptibility is derived using a multidimensional surface area density function. It includes further information on possible threats and the configuration of the considered urban environment to get insights on the local event susceptibility taking all objects in the neighborhood into account. The averaged probability of a single event at a given position is estimated using within a Gaussian distribution the distance to urban objects.

The basis for the vulnerability estimation builds the implementation of established physical and engineering models. Pre-defined building types are considered for the approximation of a given surrounding and allow an evaluation of personal and structural damage. In comparison with existing risk assessment schemes, the present methodology considers multiple positions and multiple magnitudes of possible threats as well as threat types. Therefore, the presented assessment scheme results finally an absolute overall risk in alignment with historical data and not only in a worstcase result for a single threat event or set of critical events. The application of historical data for terrorist explosive events shows a higher frequency of scenarios with smaller intensity. These empirical facts influence the weighted vulnerabilities and result in lower vulnerabilities in opposite to worst-case views.

A comprehensive investigation of the whole urban environment allows the identification of weak spots, that is not only critical infrastructure elements are considered. Assessment of monetary damage is a further type of consequence, which can be easily estimated. This scheme can form the basis for a cost-benefit calculation for the sustainable and robust design of urban environments. The relative risk reduction information and loss estimation bring information for the quantification of gain of resilience in terms of reduction in susceptibility and/or vulnerability as well as risks. The quantitative assessment of enhancement measures demonstrates their effectiveness.

This generalized scheme is suitable for a wide range of threats when using associated hazard and damage models. In particular it was indicated how to use CFD simulations for more accurate hazard propagation simulation. The susceptibility assessment can be applied to quantify the resilience management phase prevention. The vulnerability covers the phase protection and response, and all these quantities for the preparation phase and to some extent also the response and recovery phases, the present approach contributes to quantifying resilience. Further research should be done in the range of response and recovery processes to reach the goal of a quantitative measure of resilience.

The presented results are implemented in in a demonstrator as a result of a research project VITRUV [20], which is further developed within the project EDEN [28]. The 3D visualization of the prototype generates a user-friendly support for decision makers. Currently the approach is used to evaluate terroristic threats for scenarios with biological, chemical and explosive agents. To follow up the idea of a generalized approach for a wider range of hazards, further investigations in the range of natural disasters are considered as a useful extension of the existing approach.

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International Journal of Protective Structures, Vol. 7, March 2016 by SAGE Publications Ltd, All rights reserved. (c) [The Authors]

Appendix

Table 2: Overview of used and pre-defined building types.

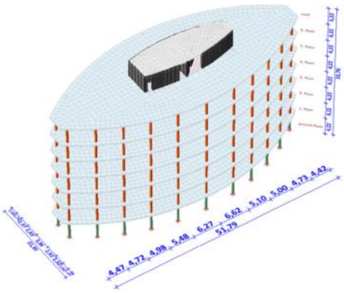
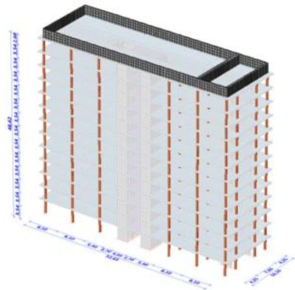
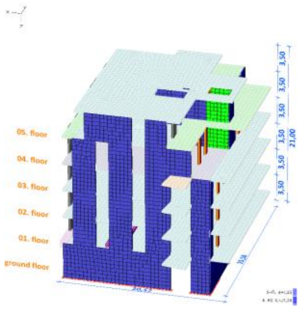
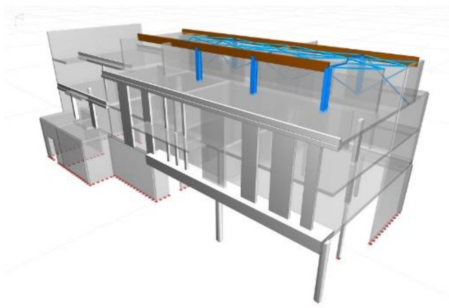
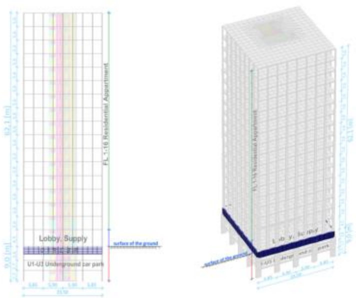
Type		Material, construction
	Office building	Reinforced concrete, Framing construction
	Office tower	Reinforced concrete, Framing construction
	Multi-family house	Reinforced concrete, Mixed structure of walls and columns
	Multi-family house, mixed usage	Reinforced concrete, Ground level with commercial use, upper level with residential use
	Block of flats	Reinforced concrete, Entrance with lobby, columns span over two floors

Table 3 presents the building attributes of the application example. The dimension and the number of floors in combination with the building usage (pre-defined person density) quantifies the number of persons per building. The construction type builds the basis for the structural response assessment. The last two columns of Table 3 include the usage and region dependent empirical frequency and consequence. The values are based on an analysis of the Terror Event Database. Details are published in [36]. The presented application example uses empirical data of Western Europe. The frequencies and consequences include all possible threat types, like explosive events, arson or armed attacks, for example.

Table 3: Overview of building attributes of the considered urban environment.

No.	**Usage**	**Construction type**	**No. of floors**	**No. of persons per building**	**Events per year and building**	**Casualties per event**
1	Corporation	Office tower	15	259	$2.5 \cdot 10^{-4}$	0.21
2	Finance, trading	Block of flats	16	119	$1.5 \cdot 10^{-5}$	0.65
3	Finance, trading	Block of flats	20	149	$1.5 \cdot 10^{-5}$	0.65
4	Agency	Office building	8	63	$4.3 \cdot 10^{-5}$	0.66
5	Agency	Office building	7	70	$4.3 \cdot 10^{-5}$	0.66
6.1	SME	Office tower	10	42	$2.9 \cdot 10^{-5}$	1.41
6.2	SME	Office tower	10	42	$2.9 \cdot 10^{-5}$	1.41
6.3	SME	Office tower	10	42	$2.9 \cdot 10^{-5}$	1.41
7	SME	Office building	6	30	$2.9 \cdot 10^{-5}$	1.41
8	Supply, disposal	Office building	6	30	$4.3 \cdot 10^{-5}$	0.12
9	Embassy	Office building	10	70	$7.4 \cdot 10^{-4}$	0.66
10	Retail, service	Office building	3	33	$3.9 \cdot 10^{-6}$	2.94
11	SME	Office tower	15	212	$2.9 \cdot 10^{-5}$	1.41
12.1	Nursing, hospital	Office building	4	759	$2.5 \cdot 10^{-6}$	1.5
12.2	Nursing, hospital	Office building	3	69	$2.5 \cdot 10^{-6}$	1.5
13	Religion	MFH+	4	37	$1.5 \cdot 10^{-6}$	3.13
14.1	Residential	MFH	5	46	$6.2 \cdot 10^{-8}$	0.27
14.2	Residential	MFH	5	20	$6.2 \cdot 10^{-8}$	0.27
14.3	Residential	MFH	5	20	$6.2 \cdot 10^{-8}$	0.27
14.4	Residential	MFH	5	20	$6.2 \cdot 10^{-8}$	0.27
15.1	SME	Office building	10	61	$2.9 \cdot 10^{-5}$	1.41
15.2	SME	Office building	10	61	$2.9 \cdot 10^{-5}$	1.41
16	Retail, service	MFH+	4	89	$3.9 \cdot 10^{-6}$	2.94
20	SME	Office tower	10	45	$2.9 \cdot 10^{-5}$	1.41