Statistical driven Vulnerability Assessment for the Resilience Quantification of Urban Areas

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ABSTRACT: The formation of new threats and the increasing complexity of infrastructure elements underline the need for more robust and sustainable systems, which are able to cope with adverse events. Achieving sustainability requires the increase of resilience. Currently, a comprehensive approach for the quantification of resilience is missing. Within this paper, a new generalized mathematical framework is presented to assess the resilience of complex systems, like urban areas. A clear definition of terms and their interaction builds the basis of this assessment scheme. Risk-based approaches are extended with the dimension of time, to quantify the susceptibility, the vulnerability and the recovery behavior of complex systems for multiple threat scenarios. Engineering approaches are applied to assess expected damage effects and are combined with statistical methods to weight the probability of occurrence and the exposition of the investigated system to the source of disruptive events. Resilience is covered by indicators for preparation, prevention, protection, response and recovery. The presented approach is able to determine these indicators and provides decision support, which enhancement measures are more effective. Hence, the framework quantifies, if it is better to avoid a hazardous event or to tolerate an event with an increased robustness, for example. An application example assesses urban areas with consideration of multiple adverse events, like terrorist attacks or earthquakes, and multiple buildings. Each urban object includes a certain number of attributes, like the object use, the construction type, the time-dependent number of persons and the value to derive different performance targets. The assessment results in the identification of weak-spots through the evaluation of single resilience indicators.

1. INTRODUCTION

Sustainable socio-economic urban developments require the availability of infrastructure and buildings. Current observations show that agglomerated areas comprise a high degree of critical infrastructure and that systems will become more complex and interconnected (The Minerals, Metals and Materials Society (TMS), 2012). Due to this change, the failure of a single element increases the probability to produce cascading effects with unexpected consequences (Kröger & Zio, 2011) as well as emergent threats.

Besides the increasing complexity, a further challenge for urban areas lies in an increasing population growth (Department of Economic and Social Affairs, 2014) and the formation of new threats (Branscomb, 2006), which can have a lasting effect on the hazard vulnerability and resilience (Cross, 2001).

Classical risk assessment schemes (Kaplan & Garrick, 1981) can give answers to the questions:

- What can go wrong?
- How likely is it that it goes wrong?
- What are the (immediate) consequences, if it happens?

Such evaluation methods quantify the acceptance of expected losses and require the definition of a decisive scenario. Unknown events cannot be evaluated and a time-dependent assessment before, during and after a disruptive event is not evaluable with such approaches.

Within this paper, selected results from (Fischer, 2018) are presented, where different approaches are compared and consolidated to propose a novel framework with the aim to quantify the resilience of urban areas. This methodology fills the gap to define a risk-based consequence driven and time-dependent approach for the evaluation of urban surroundings.

2. GENERALIZED FRAMEWORK

Based on the interdisciplinary research in the field of resilience, there are different interpretations concerning the definition and of that term (Adger, 2000). Within the present work, the five phases of the resilience cycle according to (Thoma, 2014) are used as definition. Therefore, resilience is:

"The ability to repel, prepare for, take into account, absorb, recover from and adapt ever more successfully to actual or potential adverse events. Those events are either catastrophes or processes of change with catastrophic outcome, which can have human, technical or natural causes."

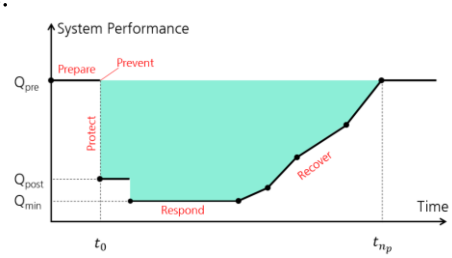

Figure 1: Resilience phases and their interpretation within a performance-time relation for the quantification of resilience (Fischer, 2018)

The integration of a performance loss over time relation can be used to describe the resilience of a system before, during and after a disruptive event (Bruneau, Chang, & others, 2003), as indicated with the green area in Figure 1, i.e. a smaller area results in a more resilient system.

Single resilience phases of the definition can be measured concerning their effectiveness within that functional behavior. As indicated in Figure 1, measures of preparation and prevention will extend the time before disruptive events or avoid them completely. The drop of the system performance indicators is a measure of the level of protection and vulnerability. Note that typically the conduction of the protection measures are often even conducted before the prevention measures but show during and after the threat event occurs.

Efficient response decreases the degree of disruption and helps to start to bounce back quickly after the shock event. Finally, the resilience phase recovery describes all the aspects of relaxation, recovery and possible learning and the preparation for future events.

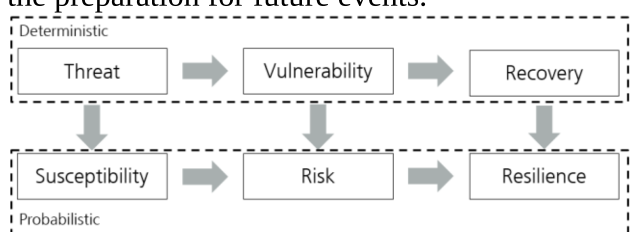

Figure 2: Proposed framework to assess a performance-time relation as basis for resilience quantification (Fischer, 2018)

To derive a performance target over time, as shown in Figure 1, a novel framework is defined, which includes several components.

Figure 2 presents the methodology. The assessment scheme can be separated into two main parts. Under the assumption of a threat occurrence, the deterministic part uses physical models to quantify the intensity of a hazard source and the corresponding damage effects (vulnerability). A certain degree and certain number of steps of recovery are required based on the resulting damage effects.

The deterministic realm is applicable to derive a performance-time relation for a single threat, but requires the definition of a decisive scenario. Based on uncertainties that a certain threat event occurs, the deterministic part is coupled with a probabilistic realm. Stochastic methodologies are applied to evaluate the frequency and the exposition to a threat within the susceptibility approach.

The combination of susceptibility and potential damage effects results in a risk-based vulnerability. Averaged results for multiple threat scenarios moves the approach from a scenario driven to a consequence based analysis for the identification of weak spots. The combination of weighted (risk-based) vulnerabilities and corresponding recovery processes consider a multitude of random scenarios and results in an averaged performance-time relation to characterize the resilience of a system.

3. MATHEMATICAL FORMULATION

In alignment to the introduced framework in Figure 2, an abstract model of an urban area U is defined as a superset including a finite number of subsets, like free spaces $a_m, m = 1, \dots, n_{area}$ or buildings $b_k, k = 1, \dots, n_{building}$.

A single building b_k is characterized by a position $\vec{r}(b_k)$, a spatial extension dimension $L(b_k)$ and a type of object use $u_l(b_k), l = 1, \dots, n_{object\ use\ type}$, like residential or office, for example.

A security relevant event, such as an explosion source or an earthquake within or close to an urban environment is defined as threat T_i. A threat can have different forms and the various threat types are expressed with the running index $i = 1, \dots, n_{threat}$. A threat can occur at a number $j = 1, \dots, n_{position}$ of possible locations $\vec{r}_j$. The physical hazard potential of a threat is described within a hazard model $H(T_i, \vec{r}_j; P)$ (Fischer, 2018) This model relates the threat type T_i and the event location $\vec{r}_j$ to the urban environment U. The physical properties are defined within the attribute parameter set P to characterize the (time dependent) hazard potential, like the magnitude of an earthquake, for example.

Depending on the intensity and the exposition, the occurrence of a threat can cause a certain type of consequences $D_g, g = 1, \dots, n_{consequence\ type}$ at different locations in the urban surrounding $\vec{r}_o, o = 1, \dots, n_{consequence\ pos}$. Possible consequences of type D_g, like direct structural or non-structural damage at a building, at location $\vec{r}_k$ are characterized within the local what-if vulnerability $V(\vec{r}_k, D_g)$. An exemplary assessment of structural building damage can be realized with the use of single degree of freedom models (Fischer, 2009) as basis for the collapse behavior of buildings (Müllers, Fischer, & others, 2015).

Based on the degree of damage or loss of functionality, a certain degree of recovery is required to reach normal community activities and the initial performance of the investigated system, like an urban environment. The rebuild and recovery function $Q_{n_p}(t)$ characterizes the time-dependent behavior as a stepwise linear function considering $n_p, p = 1, \dots, n_{phases}$ recovery phases, as sketched in the diagram in Figure 1.

This causal chain of threat occurrence, resulting vulnerability and required time-dependent recovery for each threat event is summarized as

$$H(T_i, \vec{r}_j; P) \rightarrow V(\vec{r}_k, D_g) \rightarrow Q_{n_p}(t) \qquad (1)$$

and expresses the deterministic part of the introduced methodology in Figure 2. This mathematical expression is valid to describe arbitrary threat types and investigated systems. The application of physical or engineering models results in quantitative measures as basis for decision makers. For an arbitrary building type and damage level, a recovery function with respective recovery phases is defined, e.g., by resorting to typical planning and construction times and respective subsystem availabilities.

The prediction of a single threat type scenario can be fraught with inaccuracies because it is difficult to estimate the threat position and the threat intensity can vary. Based on this fact and in alignment to the generalized framework in Figure 2, the frequency that a certain threat T_i occurs at a certain position $\vec{r}_j \in A_j$ is summarized within the local susceptibility $S(T_i, A_j)$ and hence the causal chain in equation (1) can be weighted with a probability that such an event occurs on A_j in the urban surrounding. This step incorporates the probabilistic realm of the assessment scheme.

The introduction of an averaged time-dependent recovery process (equation (2)) considers multiple threat types and intensities (index *i*), threat positions (index *j*) and urban objects (index *k*). Each combination is weighted with the corresponding susceptibility $S(T_i, A_j)$. Equation (2) quantifies the averaged loss and recovery with respect to all possible threat events and urban objects, if a single event occurs:

$$Q(t; n_p, D_g) = \sum_i \sum_j \sum_k Q_{n_p}\left(t \middle| V\begin{pmatrix} H(T_i, \vec{r}_j; P), \\ \vec{r}_{b_k}, D_g \end{pmatrix}\right) \cdot S(T_i, A_j) \quad (2)$$

The summation of the performance-time relations in equation (2) results in an averaged time-dependent single quantity to describe the resilience of urban environments. The recovery function Q for a single scenario is characterized by the deterministic part of the framework in Figure 2. The consideration of multiple scenarios and the corresponding probabilistic susceptibility weighting transfers the approach from a single scenario driven to a consequence based approach. Based on a multi-event based averaged risk expression also a multi-event (multi-scenario) based overall averaged resilience expression is constructed.

In alignment to the definition of resilience (Figure 1), a single quantity can be reached by integration over single intervals of the stepwise linear recovery function, see equation (3). The integrated performance loss is related to the time of disruption $\left[t_1, t_{n_p}\right]$ to consider the gradient of recovery within the defined metric.

$$R_Q = \frac{1}{Q_{max}\left(t_{n_p} - t_1\right)^2} \sum_{p=0}^{n_p-1} \int_{t_p}^{t_{p+1}} \left(Q_{max} - Q(t)\right) dt \quad (3)$$

The introduced framework combines statistical data and physical approaches to evaluate urban environments with respect to the region and the geo-spatial information of the urban surrounding as well as properties of single urban objects, like the object use, constructional details, person densities or the asset value.

Single elements of the introduced approach are validated in (Fischer, 2018) and enable a postulation of a resilience quantity for an arbitrary city. Furthermore, single resilience phases, like preparation, prevention, protection or recovery can be evaluated with this structured methodology. In particular, the susceptibility quantity, a generalized frequency of event and exposure measure, is an indicator for preparation and prevention, the vulnerability quantity, a generalized damage expression, characterizes robustness and the recovery quantity characterizes response and recovery.

The presented framework intends to provide a quantitative methodology to achieve more robust and sustainable cities. Subsequently, different resilience phases and urban forms are investigated with the introduced approach. Based on the fact of a growing urbanization, the results should give insights for a sustainable growth of agglomerated areas.

4. ANALYSIS EXAMPLES

Based on published results (Fischer, Häring, 2016) concerning the susceptibility and vulnerability components of the introduced framework (Figure 2), terroristic explosive events are exemplarily evaluated to apply the presented methodology. Statistical data from the Terror Event Database (Fischer, Siebold, 2014) are combined with engineering models to evaluate the structural damage of pre-defined construction types (Müllers, Fischer, & others, 2015).

The introduced susceptibility $S(T_i, A_j)$ evaluates the probability that a certain threat T_i, e.g. an explosive event, occurs at location $r_j \in A_j$. S is derived as a multivariate density function and combines the geospatial information of the considered urban surrounding and empirical frequencies depending on the region, the object use and threat type (Fischer, 2018) Figure 3 shows the evaluation of different possible threat locations in an urban surrounding. The color codes visualize the normalized susceptibilities and give the information concerning the highest probability of occurrence, if a single event occurs with respect to all buildings, threat types and threat positions within the city model. Based on the multitude of possible scenarios, this approach builds the basis for a consequence driven assessment scheme for the physical characterization of expected losses. Besides the empirical frequency analysis, neighboring effects or the exposition to hazardous events can be considered with the connection to geospatial information of the investigated city model, which builds the basis for a weak spot identification.

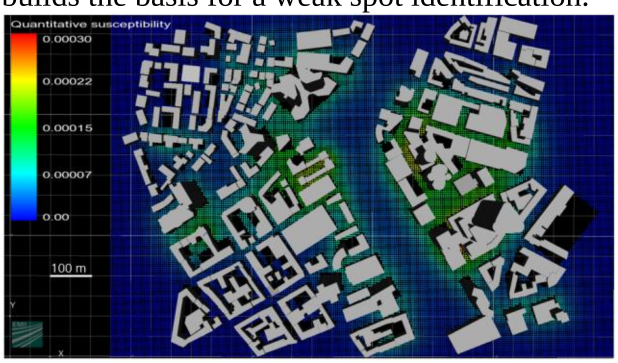

Figure 3: Combination of statistical data with geo information of a city model to assess potential threat positions within the susceptibility analysis.

According to the introduced framework in Figure 2, the next step includes the assessment of vulnerabilities. For each combination of threat type, threat position and investigated building the hazard model $H(T_i, \vec{r}_j; P)$ is derived and afterwards the vulnerability $V(\vec{r}_o, D_g)$ at building location $\vec{r}_o$ of damage type D_g, e.g. the breakage of windows or the collapse of buildings.

For a certain threat at a single location, the number of damaged buildings are counted and assigned to the corresponding susceptibility that such an event occurs.

All combinations of threat types, locations, buildings and corresponding probabilities can be cumulated and summarized within a frequency-number diagram. The result is shown in Figure 4 as the black curve. The comparison to risk criteria shows information concerning the acceptance for the investigated city.

If weak spots are identified, the application of resilience enhancement measures can be evaluated concerning their effectiveness.

The realization of a road block or bollards reduces the probability that a hazardous event occurs in front of a critical object and is assigned to the resilience phases of preparation and prevention. The black dotted line in Figure 4 shows the result where a decreased susceptibility on the ordinate and a similar vulnerability on the abscissa is observed.

The application of retrofit measures, like security glazing or other structural resistance enhancements will increase the robustness and results in smaller maximum damage effects. The result is visualized with the blue curve in Figure 4, where the curve moves on the abscissa in the uncritical range.

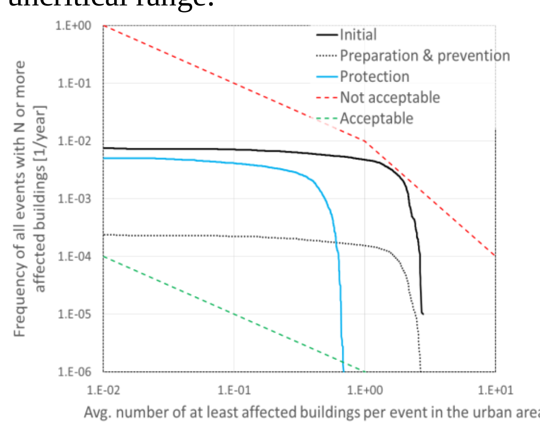

Figure 4: Combination of statistically cumulated susceptibilities with expected building damage values based on engineering models, to assess the risk

acceptance of an urban surrounding and the effectiveness of single resilience phases within an F-N diagram.

Besides the evaluation of single resilience phases, the approach can also compare the resilience of different urban areas depending on the morphology (Fischer, Hiermaier, 2018)

Figure 5 compares three typical urban forms concerning their composition of construction types and building use types. The comparison of a compact and a linear city investigates the resilience concerning the physical footprint, i.e. the building density and the distribution of urban zonings. The central business district is considered to focus on the composition of construction types and object use.

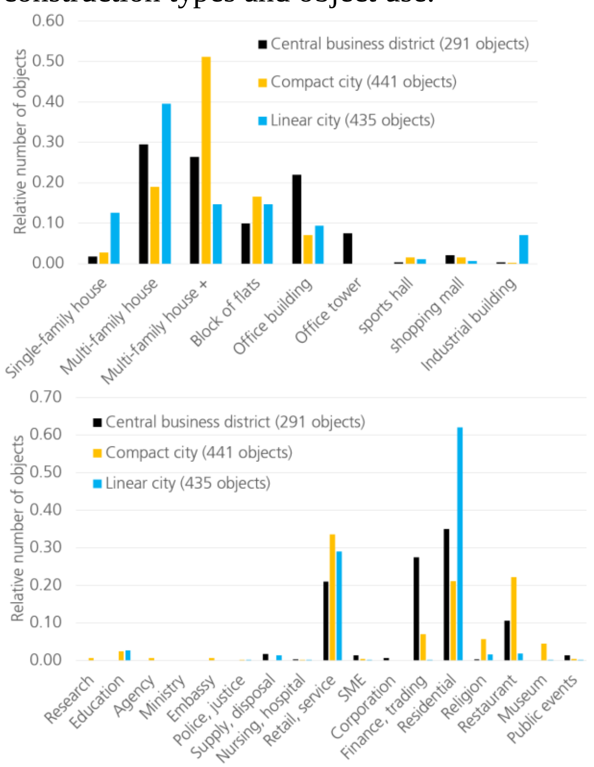

Figure 5: Distribution of construction types (upper diagram) and object use types (lower diagram) depending on the investigated city model.

The linear city includes a higher proportion of residential zonings with simple construction types, like single-family houses. Based on the high connectivity and the mixture of different use types, the compact city includes a high degree of multi-family houses with commercial use in the ground floor ("multi-family house +" in Figure 5). Characteristic for a district with specific task assignment, the central business district includes an increased number of office buildings and office towers and corresponding use types in the range of finance, trading, retail and service.

Based on the foregoing susceptibility and vulnerability analysis, equation (2) is applied for each city model and visualized in Figure 6. The results give the weighted information about the expected loss of building usability and required recovery effort if a single event occurs with respect to all possible threat types, threat positions and urban objects.

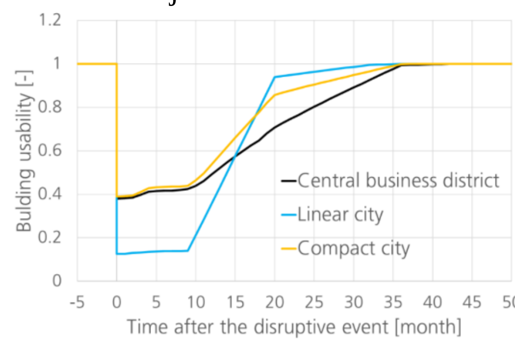

Figure 6: Comparison of different performance-time relations for different city models based on certain combinations of construction type and building use.

The linear city results in high vulnerabilities and the strongest drop of performance at the time of the impact. The compact city and the central business district show a smaller discontinuity and underline a robust behavior. Full recovery time of the building usability of the central business district is twice as long as in case of the linear model, which itself shows a relative short recovery behavior. This holds because high-rise buildings have a longer construction time than multi-functional and single-family houses. The mixture of different object and construction types of the compact city is also reflected by the performance-time relations.

The application of equation (3) results in a single quantity concerning the averaged performance loss per time and enables a comparison between different city models. Simple construction types with a corresponding short recovery time for the linear city ($R_Q = 0.27$) result in an equal quantity compared to the central business district ($R_Q = 0.26$) with a robust behavior and smallest risk quantities. A great variety of construction types and object use types within the compact city results in the best behavior regarding the resilience ($R_Q = 0.22$). This is a very interesting result, since the compact city is also favored from many other perspectives including sustainability and quality of living.

The three application examples underline the benefit of a susceptibility and vulnerability driven and risk-informed resilience assessment. The extension on the further dimension of recovery allows a more precise and deeper evaluation compared to classical risk assessment schemes.

Low vulnerability or a high susceptibility result in critical risk values. However, in combination with short recovery phases, such systems can still be comparatively resilient despite critical risk quantities. From an overall risk perspective, the costs of the overall recovery phase have to be quantified adequately. From a comprehensive resilience management perspective, classical susceptibility, vulnerability and risk cover only parts of the resilience management cycle. An important finding for the present sample case is that a correlation between risk and resilience is not mandatory.

5. SUMMARY AND CONCLUSION

Within this paper, a novel methodology is introduced to quantify the resilience of urban areas. The combination of statistical data, engineering models and time spans for potential recovery processes allows a quantification before, during and after disruptive events. The combination of risk quantities and recovery processes deliver a time dependent estimation of expected averaged performance loss as well as resilience.

The approach covers the phases preparation, prevention, protection and recovery, which can be directly matched and evaluated concerning their efficiency using the quantities proposed. The resilience phase response is indirectly matched. For instance, an increased robustness results in smaller damage effects and hence in smaller efforts concerning response and recovery.

Three typical urban forms by variation of geospatial properties and the combination of construction type and object use are investigated with the introduced approach. Based on the multi-dimensional and complex characteristics of a certain city type, generalized statements about a most effective resilience improvement measure are not available and require an individual investigation per city and the examination of different resilience phases. If the assessment results in relatively high susceptibilities, preparation or prevention measures will be more powerful. Protection measures are adequate, if the considered system exhibits high vulnerabilities. Decreasing damage effects result in smaller recovery efforts and require lower efforts concerning the response.

The response and recovery perspective, with focus on reconstruction, offers the additional quantification of resilience in terms of recovery times, recovery slopes and expected performance loss. A steeper slope of the performance function results in a faster recovery and is considered in the applied expression to give an idea of rapidity within the recovery phase. The introduced formulation in equation (3) results in a single quantity and gives the option of comparability between different cities or resilience improvements. The extension to recovery as a further resilience dimension shows that decreasing susceptibilities and increasing robustness or combined low risk values alone are not sufficient to qualify resilient systems.

Building density, the distribution of objects, free spaces, construction types and the use of buildings are main attributes, which influence the resilience of an urban surrounding. The results deliver information on how growing agglomerations can be sustainably designed also with regards to new threats. The overall framework and calculation methods builds a possible basis for urban planners, decision makers or insurance companies to analyze and optimize designs of city areas.

Within this paper, terroristic threats are exemplary evaluated. Based on the clear definition, this framework allows also an evaluation of other main kinds of disasters. This requires the availability of statistical data and appropriate models to assess expected damage effects. Examples could be models in the range of earthquake events (Krawinkler & Miranda, 2004) or flood risks (Büchele, Kreibich, & others, 2006).

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