From event to performance function-based resilience analysis and improvement processes for more sustainable systems

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Abstract: Rising extremes and varieties of threats towards socio technical systems ask for improved overall risk control and resilience enhancement. Most current classical approaches focus on the assessment of single or multiple threat events countering system objectives. However, more recent approaches ask for the identification, determination and use of time-dependent system performance functions and their assessment in case of disruptions. Thus, the paper discusses advanced risk and resilience analysis approaches for explosions, terroristic events in urban spaces, cascading effects in coupled supply grids, scoring of critical infrastructures, and tabular resilience analysis and management. Summarising respectively the main processes, methods for steps and results, it argues how time-dependent system performance function resilience approaches allow a more direct quantification of overall risk control objectives, since it assesses main system service functions before, during and post disruptions. The approaches are well suited for communication with the public, management and dashboard mobile visualisation.

Keywords: explosive quantitative risk analysis; terrorism susceptibility and vulnerability; coupled supply grid analysis; quantitative resilience scoring; tabular risk and resilience analytics; system (non) performance function; terrorism susceptibility; semi-quantitative residence analytics.

Reference to this paper should be made as follows: Häring, I., Schäfer, J., Vogelbacher, G., Fischer, K., Riedel, W., Faist, K., Finger, J., Fehling-Kaschek, M., Scharte, B., Ross, K., Restayn, E-M., Stolz, A., Leismann, T. and Hiermaier, S. (2021) 'From event to performance function-based resilience analysis and improvement processes for more sustainable systems', *Int. J. Sustainable Materials and Structural Systems*, Vol. 5, Nos. 1/2, pp.90–120.

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Johannes Schäfer received his Bachelor from Offenburg University and a Master from Technical University Munich (TUM) in Mechanical Engineering in 2012. In the same year, he started working at Fraunhofer EMI mainly in the field of expert tool development focusing on simulation algorithms. His application domain is quantitative hazard and risk analysis, in particular accidental explosions and demining. He was a main technical and scientific Fraunhofer EMI contributor in the EU projects D-BOX on civil demining, EDEN covering tools for CBRNE analysis and management, ENCOUNTER on countering explosive sources in urban areas, and in a project of the Geneva International Centre for Humanitarian Demining (GICHT) on the software supported analysis of moving explosive hazard sources.

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This paper is a revised and expanded version of a paper entitled 'Technical approaches to resilience for sustainable systems: from event to performance function based analysis and improvement processes' presented at the 2nd International Workshop on Resilience 2018 (IWR2018), Nanjing and Shanghai, China, 31 October to 2 November 2018.

1 Introduction

The complexity of systems increases through interconnectedness, self-learning, intelligence, advancement in subject domains and level of integration. This is mainly driven by increasing functionalities expected by users whilst also meeting high standards regarding availability, reliability, safety, security, low environmental and CO_2 footprint, individual and societal acceptance. Systems may range from simple technical to large-scale socio cyber-physical systems, e.g., from single automotive cars to critical infrastructure systems or urban quarters.

At the same time, modern systems are exposed to an ever-increasing number of in parts novel threat type modalities and an increasing level and variance of such threats. Novel threat types include, for instance, varieties of cyber-attacks, e.g., any substantial zero exploits, or machine-learning and artificial intelligence driven attacks. Attacks with increasing variability include weather phenomena hitherto almost unknown in the more northern hemisphere, e.g., (mini) tornados, heat waves and draughts, but as well-educated terroristic attacks. A novel type is also the educated combination of threats that use the weakness of systems due to natural disasters to launch additional physical or cyber-attacks, e.g., physical-cyber-attacks on dams during flooding events.

In addition, ongoing trends need to be considered such as ever shorter product cycles, obsolescence problems, high ambitions for development cost reductions, slim and just-in-time production, high economic and reputation losses in case of quality issues and increasing digital and virtual system developments with decreasing real field tests. Thus, the need for a more efficient risk control becomes obvious as well as for a systematic resilience development, at least with respect to any threats known in advance to take advantage of better overall risk control before, during and post potential failures and disruptions of systems.

The present text reviews and discusses several approaches for risk control and resilience in the domains of countering terroristic threats, vulnerability of urban areas and critical infrastructure resilience. Threats considered include terroristic threats in urban areas and all types of threats that affect critical infrastructures, in particular anthropogenic (e.g., climate-change related) and man-made (e.g., accident, sabotage, terroristic, state-supported) threats.

Resilience engineering in the present work is defined as a major extension of classical risk analysis and management by taking all phases of the resilience cycle into account (Thoma et al., 2016) to achieve overall risk control of socio-technical systems. It covers various scales, from devices up to critical inter-continental infrastructure systems and aims at better preparation, protection, prevention, response, recovery, adaption and learning of systems in the advent of damage events, disruptions up to crises taking account of accidental, natural-technical, natural, anthropogenic and malicious (e.g., terroristic) events (Häring et al., 2016). Resilience engineering in the present context is understood as a technical-engineering approach driven by and integrating the humanities, e.g., by considering organisational, decision making and operator behaviour models, see e.g., Häring et al. (2017).

As will be seen in the application examples for system performance function based risk and resilience quantification, improvement and development, a thorough system context and system understanding is key for successful approaches. This requires to cover also the organisational and societal context of the analysed systems. All approaches presented, aim at better overall risk control of sample systems before, during and after disruptions. Hence, they need to significantly contribute to any of the resilience cycle timeline or logic phases; for instance, preparation, building protection, detection, (active or passive) prevention, absorption, response and stabilisation, recovery, restoration and adoption, learning and improvement. The paper addresses these aspects from a technical perspective while taking interdisciplinary insights of the humanities into account.

The text is structured following the historic development starting out with classical risk analysis and management (see Section 2) of single events covering effects of events on recovery and response without quantifying these effects. It is extended in Section 3 formally to consider system recovery, in this case of the built environment. Section 3 provides an approach to consider thousands of possible potential terror events for urban terrorism risk and resilience recovery assessment. By considering multiple probability-weighted events, averaged susceptibilities, vulnerabilities, risks as well as recovery behaviours become accessible.

Section 4 provides a scheme how to assess the criticality of single components of coupled electricity, water and telecommunication grids by systematic fault insertion, fault propagation and consequence observations. Section 5 discusses an approach for semi-quantitative self-assessment and self-scoring of critical infrastructures based on an extensive adaptive questionnaire. Section 6 covers a concept for a semi-quantitative systematic tabular approach to assess risk and resilience of telecommunication grids.

Section 7 provides a tabular summary and comparison of the approaches as well as an outlook on future application options of advanced performance-based risk and resilience assessment schemes.

2 Risk and resilience analysis and management of attack vectors of explosive events

The physical robustness and resilience of urban environments regarding explosive events (accidental or intentional) are highly perceived issues regarding civil safety and security of modern societies. Examples include: industrial on-site explosions, (green) gas explosions or terrorist attacks such as suicide bombings.

In particular, the new attack strategy of multiple, simultaneous and maliciously time-coordinated events includes a variety of dangerous event types. For example, using several improvised explosive devices (IEDs), the informed use of industrial sites for the multiplication of the effect of IEDs, or the employment of house bombs, i.e., built structures filled with explosives.

The approach of Häring et al. (2018) as partially developed in the EU projects ENCOUNTER (2019), D-BOX (2019) and EDEN (2019), see also Ross et al. (2016), shows a comprehensive, tailorable and stepwise process to assess such defined event scenarios, see also further details in Salhab et al. (2011a, 2011b). It includes methodologies for the following risk and resilience quantification and improvement steps:

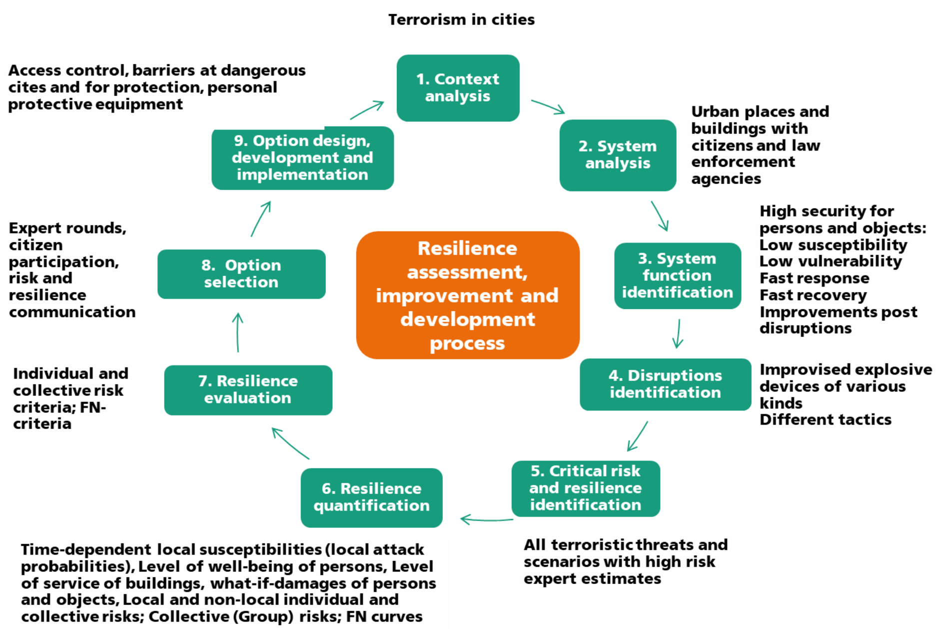
1. Assessment of the geo-spatial and local scenario.
2. Threat selection.
3. Hazard analysis for single events (simple and complex blast loading and fragment loading) based on the assumed hazard source.
4. Damage analysis of persons and objects.
5. Person exposure and event frequency analysis.
6. Risk and resilience quantification using steps 4 and 5.
7. Risk and resilience evaluation and decision making.
8. If scenario not acceptable: selection of scenario modifications, e.g., change of exposition, barrier at explosive or exposed sites. Back to step 1.

The focus in Häring et al. (2018) is on a summarising description of the validated best practice approach. Further improvements of the approach are currently conducted in the BMBF project SUSQRA (2019) regarding better characterisation of novel terroristic hazard sources.

When tailoring for this example, the resilience quantification and management process of Häring et al. (2017) using system performance and non-performance functions (see Figure 1, step 2), the initial question arises: what is the system? In the case of a city center, it is the overall urban environment along with its citizens. In case of an industrial area, it is the asset facility and the areas nearby.

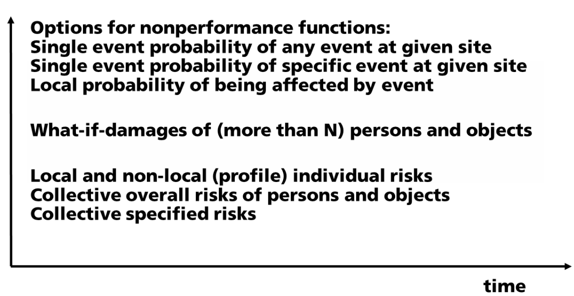
Accordingly (see Figure 1, step 3), system non-performance functions are such quantities as local risks per day, or individual local profile risks per person. They are non-performance functions since they should be as small as possible for the system. For example, the probability of a defined system degradation, expected local mean human maximum injury per day at a certain position, or an individual non-local risk profile taking the movement trajectory (exposition profile) of persons into account. Collective overall risk quantities that can be used as non-performance functions include; overall collective risks per day, collective group risks and FN-diagrams scaled to time intervals. In a similar way, what-if consequences and damage effects or overall event frequencies can be used.

Figure 1 Risk and resilience quantification and improvement process with respect to explosive events (e.g., accidents, terrorism, and natural-technical) as supported by single and multiple event risk and resilience analysis (see online version for colours)



Note: The green boxes describe risk and resilience quantification and improvement process steps. The black text gives examples for fulfilling requirements of the defined process steps.

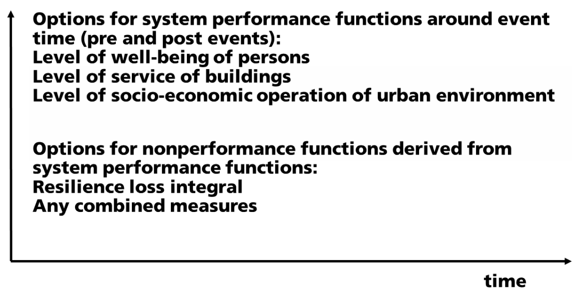
Figure 2 Examples for non-performance functions when assessing single explosive events



Note: The time dependency of the performance functions allows to determine also implicit dependencies of the functions, for instance on exposure (e.g., work-day versus public holiday), trends (e.g., due to improved physical protection and organisational means) and anomalies (e.g., increasing local terroristic threat potential).

With these definitions, a mainly non-performance function based assessment overall system risk assessment becomes feasible, see Figure 2. With the summarised approach in the steps 1 to 7 above and for a selected set of potential threats, the susceptibly of events and initial vulnerability can be assessed. They strongly depend on any changes of the scenario, e.g., easy access to the area, unfavourable geometrical changes of the scenario or increasing expositions of persons at local high-risk areas. Such changes deteriorate the mean non-performance curves.

Figure 3 Examples for system performance functions when considering single explosive events



Note: The time dependency allows to assess system properties pre, during and post events. Such assessments can be conducted for defined events, sets of events or as a weighted average of potential events.

The approaches 1 to 7 do not yet cover response and recovery performance quantification at systemic level, see Figure 3. For instance, this could be resolved at short time scales within the risk and resilience evaluation phase 6 of Figure 1 by assessing quantitatively how the city system can absorb the expected consequences, e.g., whether its hospital system can handle the expected typical fatality numbers. This also shows that the response and recovery assessment depend on many factors such as local organisational details. Also, on the time scale considered, for instance immediate rescue response versus long-term person physical and psychological recovery, building reconstruction, or even societal recovery from such events.

Within the presented approach for single events, the resilience analysis step is not much detailed, since in practical applications it is assumed that the initial damage of persons, objects and buildings can serve as a starting point for an assessment regarding the resilience response and recovery phase, e.g., to develop emergency and rescue plans. Thus, it is avoided to assume too much about the recovery and improvement efforts post events. On the other hand, resilience quantification is not conducted.

Based on the above discussion on the assessment of threat vectors of explosive events within built environments or open areas, next a formal expression is provided. It covers the main inputs required for the risk and resilience quantities R accessible within the 9-step resilience analysis and quantification process of Figure 1:

$$\begin{aligned} R_{\mathrm{g}}(\mathrm{g}) = R\Big(G, \{\rho_i = \rho(O_i, \vec{r}, t)\}, \{E_{jkl} = E(T_j, \vec{r}_k, t_l)\}, \\ \{P_{jkl} = P(G, \{\rho_i\}; E_{jkl})\}, \{H_{jkl} = H(E_{jkl}; \vec{r}, t)\}, \\ \{C_{jklm} = C\big(G, \{\rho_i\}, \{H(E_{jkl})\}, D_m; \vec{r}, t\big)\}\Big). \end{aligned} \tag{1}$$

In equation (1), R represents any risk or resilience quantity of interest, the subscript dot represents a short name of a quantity of interest and the dot between the brackets at the left-hand side quantities needed as input. The equation sign expresses that any risk and resilience quantity within the approach can be derived as an expression using the input quantities listed at the right-hand side.

In (1), G encodes the geometry of the scenario, $\{\rho_i\}_{1\leq i\leq N_o}$ the spatial and time dependent person and object distributions for a finite set of object types N_o, $\{E_{jkl}\}_{1\leq j\leq N_T, 1\leq k\leq N_r, 1\leq l\leq N_t}$ a finite set of events of N_T different threat event types at N_r different locations $\vec{r}$ and N_t different points in time t. The quantity P provides the probabilities of discrete events given the geometry and object distribution, H_{jkl} provides the physical hazard potential of each single event, and C_{jklm} determines the damage effects taking into account of N_D different damage and effect categories $\{D_m\}_{1\leq m\leq N_D}$. In all cases, the curved brackets indicate that in general, sets of quantities need to be considered.

A finite set of events is considered representing the attack vector within a single scenario that is assessed, i.e., $\#\{E_{ijk}\}$ is between one and up to several sequential events. Also, the exposition is often known in detail for predefined representative locations of persons, i.e., $\rho_i = \rho(O_i, \vec{r}, t)$ is replaced by object numbers at known locations $N(O_i, \vec{r}_n, t)$. In addition, in (1) the time of evaluation is typically restricted to times shortly after the event (e.g., minutes up to an hour) concentrating on immediate damage effects rather than considering the still remaining damage at much later times, e.g., days, weeks or months later.

When inspecting the 8-step scheme, typical examples of assessment include for instance; geometrical scenario and exposition assessment in terms of G and $\{\rho_i\}$, threat event, probability or frequency analysis in terms of E_{jkl} and P, hazard and damage assessment in terms of H_{jkl} and C_{jklm}.

Classical risk assessment resorts to expressions using probabilities and measures for consequences, e.g., the local risk of a certain damage type for an event sequence at a given time post event

$$R_{local\ risk}\left(D_m, \vec{r}, t\right) = \sum_{jkl} P_{jkl} C_{jklm}. \tag{2}$$

The dependencies at the right-hand side of (2) are as in the right-hand side of (1). However, consequences are typically computed immediately after the damage event only, i.e., the right-hand side does not consider response and recovery activities and $t \approx t_0$, where t_0 is the starting time of the event sequence. Hence, there is no true time dependence of the local risk. However, this limitation can be lifted by considering longer time scales after the event sequence took place within the resilience analysis approach of (1). In this sense, the main extension of (1) is to allow and ask for long-term consequence analysis when compared to classical risk expressions, see, e.g., (2).

F-N diagrams allow assessment of collective risks. The frequency values are obtained for discrete and increasing consequence classes by adding all probabilities with at least the consequence class considered, see e.g., Ball and Floyd (2001), Jonkman et al. (2003) and Proske (2004) for details. Such diagrams can also be used according to (1), for instance to compare short-term and long-term effects of events within a single F-N diagram.

3 Terrorism susceptibility, vulnerability, averaged risk and rebuilding resilience quantification and management

The consideration of multiple potential events is necessary in any such cases where single critical scenarios are not known, representative scenario sets cannot be identified or where more advanced quantifications including uncertainty quantifications are asked for.

A framework that is suitable for terrorism threats, accidental events and natural events (in particular earthquakes) was developed mainly in the EU projects VITRUV (2019) and EDEN and is being further developed in the German BMBF projects Urban Security 3D (2019) and SUSQRA and within the EU project INACHUS (2019). The approach is described in Voss et al. (2012), Fischer et al. (2016), Vogelbacher et al. (2016) and Fischer et al. (2018). See the VITRUV Tool (2019) for a software implementation of parts of the approach.

Considering multiple possible events, the risk and resilience assessment scheme can be described in the following steps:

1 assessment of the geo-spatial scenario and structural properties

2 potential threat type set selection, e.g., range of explosive threats, earthquake scales

3 parameterisation of representative single events, e.g., using spatial event grid of potential events with sufficient resolution for local loading parameterisation of representative events

4 frequency analysis for representative (local) events, e.g., based on empirical historical-statistical data, urban geometry and/or expert estimates

5 person and exposure analysis for representative events, e.g., using population densities.

For each representative event:

6 hazard analysis for representative events based on the assumed hazard source or loading scheme; determination of the local hazard potentials

7 damage analysis of persons and objects due to representative events taking exposure into account for each representative event

8 response analysis for each representative event

9 recovery for each representative event, e.g., redesign and reconstruction analysis

10 learning and improvement analysis for each representative event, e.g., improvements for countering terrorism and natural threats according to advanced standards.

Using analysis results of representative events, the following steps are conducted:

11 computation of local susceptibilities of all or specific event types, e.g., local absolute event frequency for any terroristic event

12 computation of local (what-if) vulnerability of persons and objects, e.g., overall local absolute vulnerability in case of an event occurs

13 computation of local risks, non-local and profile risks

14 computation of collective risks

15 response

16 recovery

17 improvement analysis for sets of threats, building types, local areas or urban morphologies

18 risk and resilience evaluation and decision making using visualisations and criteria

19 if scenario not acceptable: selection of scenario modifications, e.g., building retrofits, and go back to step 1.

In the following, some additional details of the multi-event approach are discussed. For single representative events, the hazard and damage effects are computed as in the case of assumed known events using representative event data. The multiple events are used to compute averaged quantities by weighting each representative local event of each threat type with its absolute estimated or what-if frequency (i.e., assuming an event takes place). This allows to compute averaged (what-if) susceptibilities, vulnerabilities (damage effects) as well as risks. In a similar way, i.e., weighted with the frequency of their occurrence, the rebuilding time histories are averaged leading to an averaged recovery curve for sets of buildings belonging to an urban area.

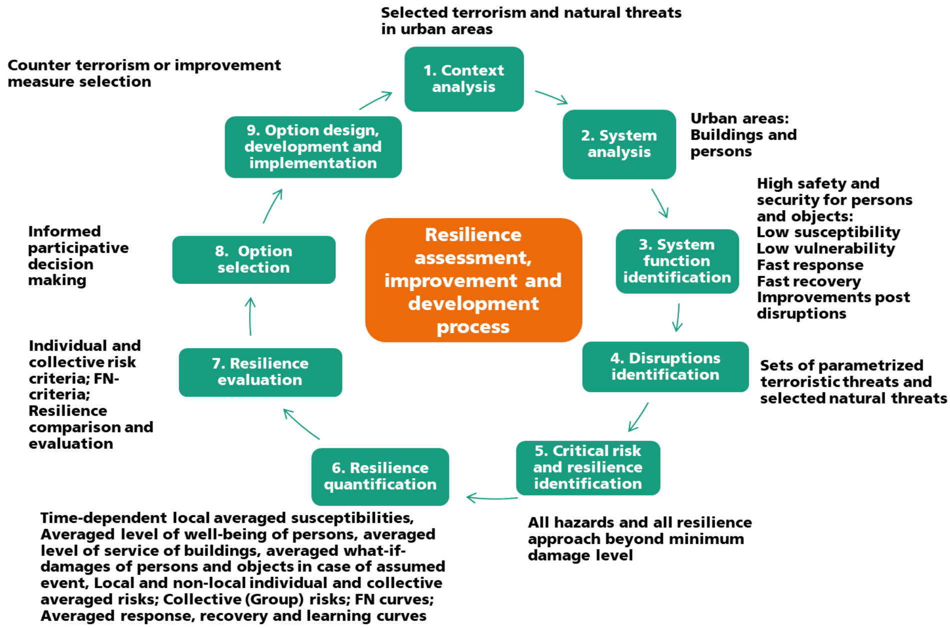
While the described Monte Carlo simulation approach as such is rather independent of the hazard sources considered, the actual hazard and damage computation requires domain knowledge. So far, it is implemented for terroristic explosive threats and is currently implemented for selected earthquake loadings. Regarding resilience quantification post events, only the recovery curve of buildings is computed.

This is conducted by assuming building phases and partial recovery steps depending on the building types and building construction and architecture guideline codes, see e.g., German Construction Tendering and Contract Regulations (DVA, 2016) and respective time duration estimates. Alternatively, historic rebuilding times could be used if belonging to sufficient similar environments. Also, societal adjustment factors could be considered. An advantage of using rebuilding times and steps according to construction guidelines is that they can be assumed as a kind of possible best practice implemented post man-made or natural events that can credibly be achieved when planning beforehand building back better.

As in the case of single events, Figure 4 asks for the system and system performance or non-performance functions that can be associated with the multiple event risk and resilience analyses. In this case, the system as well as the threat set are more concise and more comprehensive. The performance and non-performance functions are similar as in the case of considering single events, however, in each case averaged quantities are considered, i.e., cumulating weighted effects of multiple events using the local susceptibilities for each possible position of an event.

The number of representative events can be chosen such that the quantities of interest are converged. The spatial grid for positioning threats may be different from the assessment grid. It is important that the two grids fit well together and the results are converged with respect to further grid refinement.

Figure 4 Resilience quantification and development process regarding multiple possible manmade and natural threats (see online version for colours)



Note: Now averaged quantities are accessible. Uncertainty quantities are not shown.

Figure 5 shows non-performance function examples mainly before the event.

Figure 5 Non-performance quantities of urban areas in case of disruption events when considering multiple events

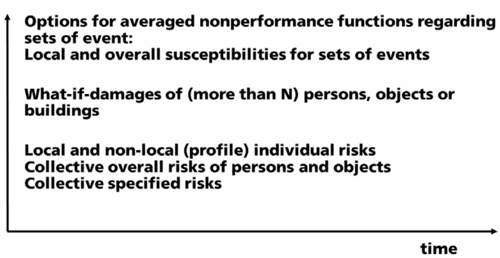
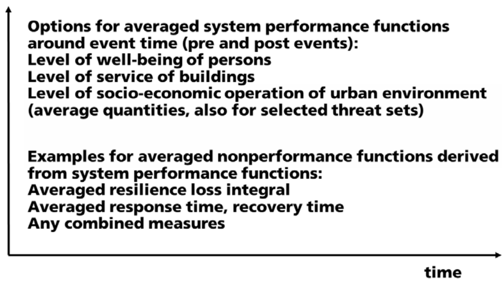


Figure 6 covers performance functions, mainly on systemic level. It is observed, that all quantities mentioned within the 19-step scheme can be sorted in non-performance and performance functions. However, only a few of them can be considered as systemic functions. Considering such systemic functions, additional quantities can be derived, e.g., duration times, loss integrals, and recovery slopes.

Figure 6 Performance functions on system level accessible using multiple representative events for assessment



Note: Examples for performance functions derived from averaged systemic performance functions, e.g., to assess the reconstruction and back-to-service times.

Overall risk and resilience quantities that are accessible when considering multiple possible event types at all possible event locations and times depend on the following quantities

$$\begin{aligned} R_{\mathrm{g}}(\mathrm{g}) = R\Big(G, &\left\{\rho_i = \rho\left(O_i, \vec{r}, t\right)\right\}, \left\{E_j = E\left(T_j, \vec{r}, \pm\Delta\vec{r}, t \pm \Delta t\right)\right\} \\ &\left\{P_j = P\left(G, \{\rho_i\}, E_j; \vec{r} \pm \Delta\vec{r}, t \pm \Delta t\right)\right\}, \left\{H_j = H\left(G, \{\rho_i\}, E_j; \vec{r}, t\right)\right\}, \\ &\left\{C_{jm} = C\left(G, \{\rho_i\}, H_j, D_m; \vec{r}, t\right)\right\}\Big). \end{aligned} \tag{3}$$

When comparing with (1), in (3) all the quantities are available at all times and all locations. In the case of events E_j and corresponding probabilities P_j, the expression $\vec{r} \pm \Delta\vec{r}$ means that the event occurs in the vicinity of $\vec{r}$ (in a compact area around $\vec{r}$) and $t \pm \Delta t$ means that the event occurs close to time t (in a symmetric interval around t).

The hazard potential H_j is available locally in space and time as well as the local damage effects C_{jm}, depending respectively on the position and time of the threat causing the hazard potential and damage effects. For evaluation, such values are cumulated considering the probability-weighted effects of single events. In general, E_j, P_j and H_j depend on the geometry and the object distribution.

Furthermore, typically the times considered for all the quantities but C_{jm} are close to threat event time occurrence, whereas the time variable of the consequences itself may stretch up to years. As shown by Fischer et al. (2018), this allows to assess the reconstruction recovery of urban arears post events.

By inspection, one infers that (3) is a generalisation of (1), when considering attack vectors with single events only. The limitation of (1) is rather limited, since so far single or few events are still the main terroristic event and earth quake type. In addition, attack vectors can be covered by increased event frequencies of the corresponding single events that form an attack vector. This is also why the susceptibility, averaged consequence, risk and resilience quantities derived from (3) can be considered as realistic approximations. However, equation (3) allows one to consider in a much more systematic way all potential events as opposed to representative scenarios as covered by equation (1).

Finally, three example equations of (3) are provided: the local event susceptibility for all types of events, e.g., for urban spaces; the local damage effects of a given damage type, e.g., on building facades, due to all types of events; and the local level of recovery taking account of all past events:

$$\begin{aligned}
&P\left(\vec{r} \pm \Delta\vec{r}, t \pm \Delta t\right) = \sum_{j} P\left(E_j; \vec{r} \pm \Delta\vec{r}, t \pm \Delta t\right),\\
&C\left(D_m, \vec{r}, t\right) = \sum_{j,\vec{r}',t' \le t-\Delta t} C\Big(G, \{\rho_i\}, H\big(G, \{\rho_i\}, E_j; \vec{r}' \pm \Delta\vec{r}', t' \pm \Delta t'\big); D_m, \vec{r}, t\Big),\\
&R\left(D_m, \vec{r}, t\right) = \sum_{j,\vec{r}',t' \le t} P_j\left(\vec{r}' \pm \Delta\vec{r}', t' \pm \Delta t'\right) C\Big(G, \{\rho_i\}, H\big(G, \{\rho_i\}; E_j, \vec{r}' \pm \Delta\vec{r},\\
&\qquad\qquad t' \pm \Delta t'\big); D_m, \vec{r}, t\Big).
\end{aligned} \tag{4}$$

For an expression of the local average level of recovery post an assumed single event distributed according to a what-if susceptibility, see Fischer et al. (2018) for further expressions and a sample implementation.

4 Coupled electricity grid, water and telecommunication grid agent-based robustness and mitigation measure assessment

The effects of local disruptions within single grids can be assessed using several types of modelling as listed below:

1. Physical-engineering grid modelling and simulation approaches: physical-engineering grid simulation approaches address the lowest level corresponding to the physical-engineering technical hardware grid, e.g., cables for electricity supply or the gas distribution tubes. Predictive models need sufficient data input, including spatial distribution, dimensions and materials, and steering details of the systems.

2. Often topological grid models are used that only consider nodes and edges. This restricts the assessment to connectivity analyses (e.g., determination of existing connections), redundancy analysis (e.g., number of disjoint connections of nodes), and $N - m$ failure analysis, where m is the number of possible failures without major system performance loss and N is the number of all components.

3. More realistic are graphical models that consider capacities of nodes and/or connections. This allows to set up basic rate equations and constraints for possible solutions. For many practical applications, this is already sufficient. The reason is that valid physical-engineering approaches as in (1) need a lot of detailed input and (often restricted) data for predictive simulation.

4. Simpler than a topological model is to consider balancing conditions for infrastructure systems, possibly with some additional constraints. E.g., a water distribution system provides water to all connected consumers, where the quantity allowed to be taken out by each user is limited to situations where the source node is operational and the total water used is less than the source provides. Such models

reflect the often limited access to information on infrastructure properties and coupling.

5 Even simpler models just consider areas covered by infrastructure systems. For instance, water supply or mobile communication is available for an area provided the water source node or the mobile radio mast or cell tower is operational. For instance, for operation, the water node might need electricity and access to water.

6 For another categorisation approach with a stronger societal-economic perspective and focus on telecommunication grids see Ouyang (2014), for a more state-of-best practice methodological categorisation focused approach see Chen and Milanovic (2017), and for a generic vista on the needs to be addressed see Kröger (2017).

In general, such models of different levels of resolution and physical-technical accuracy can be used within the same coupled grid modelling, provided the modelling interfaces are well defined. Extracting information from advanced models to provide input for more approximate models is rather straightforward.

To achieve simple averaged models from more complex system models, requires sets of subsystem states and sets of possible inputs and outputs. Such averaging models can be discrete deterministic or probabilistic. For instance, a telecommunication mast is not operational if there is no electricity versus there is a time dependent recovery probability in case of electricity loss due to the use of electricity generation with diesel generators. The former is a discrete model the latter is a probabilistic model.

In the following, an example methodology is sketched how to assess cascading (snowball) effects within coupled grids using approach 1 for an electricity grid, 4 for a water grid and 5 for a mobile phone grid by considering radio cells. This approach has been implemented in parts within the EU project SNOWBALL (2019). The approach to assess the criticality of nodes and edges can be summarised as follows:

1 set up the geo-spatial layers of the (multi-national) surface area to be considered covering geography, buildings, etc.

2 provide spatial data and grid parameters of individual infrastructure grids

3 define coupling models or agents between grid layers

4 determine coupling nodes between infrastructure types and assign coupling models

5 define user roles (agents) and interfacing models with the infrastructure, e.g., prosumer of electricity

6 assign agents to infrastructure nodes

7 run simulation of undisturbed system and confirm correct standard operation modelling

8 define attack vector, i.e., time ordered set of minor or major events affecting the infrastructure

9 insert attack vector and observe the response of the coupled infrastructure system, e.g., in terms of major overall performance quantities (e.g., number of households with full level of supply, minimum supply and no supply; percentage of service level delivered for each type of infrastructure)

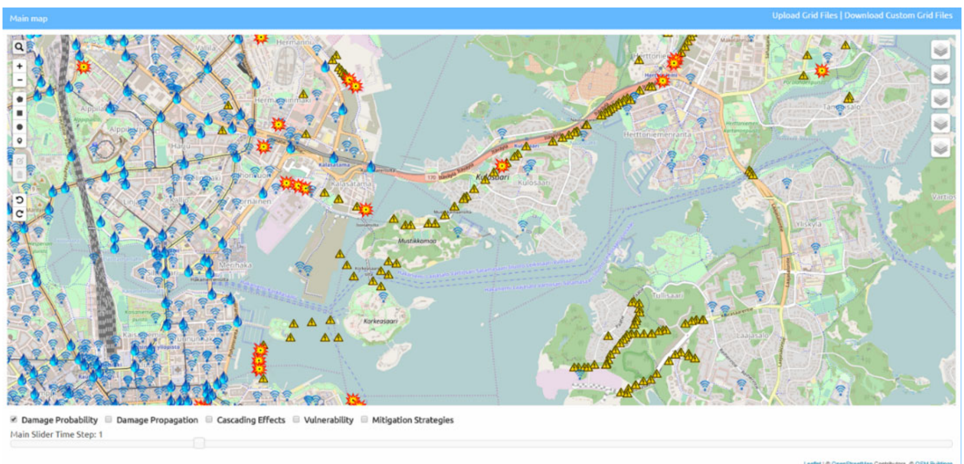
10 repeat 8 and 9 for a set of potential attack vectors of interest, e.g., all already observed types of attacks

11 determine and compute overall assessment quantities and rankings (e.g., damage effect or risk ordered set of single event attack vectors, double attack vectors, etc.)

12 select system improvement options (e.g., increase performance of nodes and edges or add additional nodes or lines in any of the infrastructure grids or modification of coupling agents).

Figure 7 shows the cascading effect of a single event (loss of major transformer station) on the water supply and the mobile radio coverage.

Figure 7 Example of the effects of a single failure on a coupled supply grid in an urban region (see online version for colours)



Note: Shown are the effects on the electricity, the water and the telecommunication grid.

From the discussion of the assessment procedure, it becomes apparent that it is capable to provide system performance and non-performance functions at various levels of abstractions:

- at single node or edge level;
- for (parts of) single infrastructure systems, e.g., regional percentage of nodes or leave (terminal) nodes (e.g., households) served;
- several layers of infrastructure, e.g., level of overall service.

From the 12-step scheme, the following generic dependencies of risk and resilience quantities can be derived:

$$\begin{aligned} R_{\mathrm{g}}(g) = R(&\{\text{Node1}\}, \{\text{Edge1}\}, \{\text{Node2}\}, \{\text{Edge2}\}, \{\text{Node3}\}, \{\text{Edge3}\}, \\ &\{\text{Connection}\}, \{\text{Operator}\}, \{\text{Prosumer}\}, \{\text{Event}\}, \{\text{Response}\}), \end{aligned} \tag{5}$$

where three different coupled grids are considered in terms of their sets of nodes and edges, e.g., {Node1}, {Edge1}, a set of connection models (agents) {Connection} for selected nodes and edges, operator agent models for operators at selected nodes

{Operator}, and similarly prosumer loads within areas and at nodes, disruptions event sets (threat vectors) and planned response sets.

Based on (5), quantitative discrete risk and resilience measures include for instance:

- the number of nodes for each level with redundancy of supply of a given degree for each type of grid
- the shortest supply line to the next source node for each prosumer node before and after the event
- the number of additional nodes that are not operational in case of an event as well as the number of lines that cannot be used (dead end edges)
- how many other grids or grid levels are affected in case of an event
- the number of prosumers without service in case of an event
- the areas without service for each grid type in case of an event
- the number of connections of each node after the event
- the number of nodes without redundant supply of any kind after the event
- the additional length of lines needed to connect each node for each grid type in case of an event
- the additional loss or cost of transport of substances or energy in case of an event
- the shortest repair time or costs in case of an event
- the number of options to build the grid back better after an event.

Inspection of the 12-step scheme and equation (5) reveals that most of the assessment quantities can be made time dependent or can be combined in single quantities evaluated at different times before, during and after events. This allows a similar transition as described exemplarily for equation (1) to performance-based risk and resilience analysis as well as the generalisation to equation (3).

5 Semi-quantitative questionnaire based self-assessment and scoring of critical infrastructures

Semi-quantitative approaches are suited for the collection and analysis of expert opinion and wider sets of informed stakeholders and citizens. Also, for the identification of risk and resilience issues that need to be further investigated, in particular of potential disruption events that are not yet considered as assessed and evaluated by consistent expert opinion. Thus, semi-quantitative assessment can be used to identify the need for more advanced quantification of risk control and resilience, in case the semi-quantitative and typically fast and efficient scoring assessment did not arrive at a sufficiently unambiguous decision.

The following presents an approach based on the 'Disaster resilience scorecard for cities' developed by the United Nations Office for Disaster Risk Reduction (UNISDR), which is also supported with spreadsheet tools (UNSIDR, 2017). It is input for the present approach that adopts, modifies and extends it to critical infrastructure systems.

The approach presented in overview takes up major ideas of the score card methodology, originally developed to determine and monitor the level of achievement of key economic goals of companies (Kaplan and Norton, 1996). Ideas taken up from the score card approach are:

- believe in and systematic search for systemic, functional and covering scores
- tasking of the users to provide self-assessment scores
- use of semi-quantitative scales and overall scales.

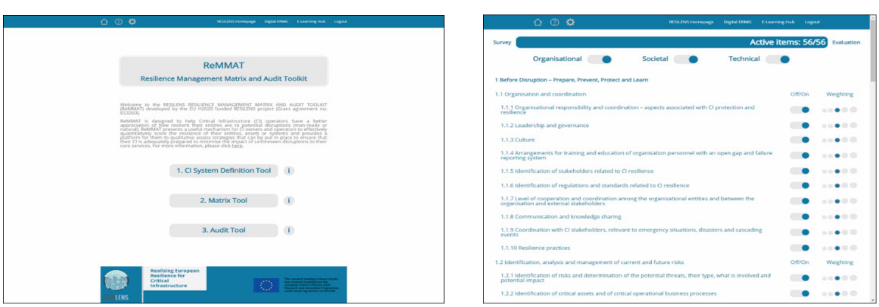
In addition, the present approach takes up typical steps as known from system analysis, system development and risk analysis. These include:

- definition of boundary conditions for improvement, e.g., time, resources
- definition of system, subsystems and connections
- risk and resilience analysis step similar to system analysis
- risk and resilience evaluation step similar overall risk evaluation step
- extensive risk and resilience improvement step in terms of selection of counter measures and their implementation
- iterative and communicative approach.

Figure 8(a) shows the structuring of the approach in three steps as developed mainly within the EU project RESILIENS (2019), in minor parts also based on results of the EU project BESECURE (https://cordis.europa.eu/project/rcn/102646/factsheet/en). For each step, questions are asked and answered, scored and aggregated. For examples of questions, see Figure 8(b). The three steps shown in Figure 8(a) correspond to classical overall system analysis steps:

1. critical infrastructure (CI) analysis
2. risk and resilience assessment and evaluation
3. improvement measures selection and implementation.

Figure 8 (a) Overview of the semi-quantitative score card approach for critical infrastructure assessment (b) Sample questions for the phase before disruptions (see online version for colours)



(a) (b)

The main difference of the approach to critical infrastructure risk assessment is that it explicitly tries to take into account of all resilience cycle phases before, during and after disruptions, e.g., according to the resilience cycle (Thoma et al., 2016) similar to disaster management cycles (Coetzee and van Niekerk, 2012). Also, other resilience dimensions are taken into account such as resilience abilities and technical resilience capabilities within the approach, see e.g., Häring et al. (2016) for further resilience dimensions and their definitions.

Figure 9(a) shows a sample radar diagram evaluation for resilience components and Figure 9(b) an example of risk control and resilience improvement measure selection. Besides a minimum set of consistency requirements, no pre-assumptions are made within the score card assessment approach, thus allowing a flexible tailoring to any infrastructure as well as threat types, in particular all types of events caused or originating from human behaviour.

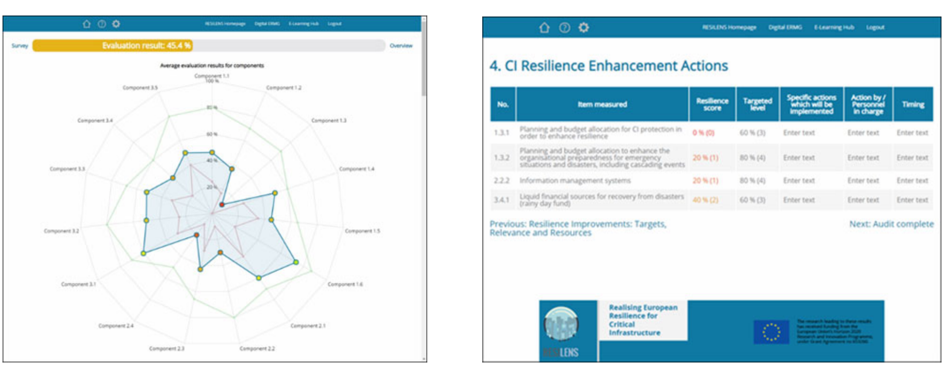
Typical scores of overall risk and resilience of a critical infrastructure read for instance:

$$
\begin{aligned}
R_{res}(\underset{\sim}{g}) &= \sum_i w_i \frac{S_i}{\Delta S_i}, \\
R_{res}(\underset{\sim}{g}) &= \sum_i w_i \left(\frac{S_i}{\Delta S_i} \geq S_i^{crit} \right)_I ,
\end{aligned}
\tag{6}
$$

where i is a (multi) index labelling any overall risk control or resilience aspect deemed of interest during the self-assessment and scoring process. The quantities $\{S_i\}_{1 \leq i \leq N_S}$ are scores for each aspect, $\{\Delta S_i\}$ are scales for each score and $\{S_i^{crit}\}$ are critical values for each scaled score, which are used within an index function. The contributions of the scores are weighted with the positive numbers $\{w_i\}$. In (6), the addends and the sum can be normalised, but need not be normalised.

For instance, for critical infrastructure context and system understanding, scores may cover the level of completeness of legal requirements considered and their level of application in the system design, the completeness of system knowledge, and the level of understanding which system functions require which subsystems of socio-technical infrastructure systems.

Figure 9 (a) Example for scoring of critical resilience components using a radar diagram
(b) Example for selection of risk control and resilience improvement measures
(see online version for colours)



(a) (b)

System risk control and resilience assessment completeness (i.e., covering all relevant aspects) may be achieved by considering single or in combination the coverage of resilience cycle phases, layers of the infrastructure (physical, technical, cyber, organisational and societal) and technical resilience capabilities (e.g., sense, represent and model, infer, act, improve). Thus, the multi-index can label all aspects using such resilience dimensions and then counting the respective resilience scores for each index combination to assess the level of completeness.

In a similar way, risk control and resilience improvement options may be labelled. In addition, for instance scores can be added regarding the feasibility and expected cost efficiency of selected counter measures.

6 Towards semi-quantitative tabular and quantitative grid assessment of risk and resilience of telecommunication grids

The approach presented in this section resorts to the rich success story of tabular system analyses, which are represented by the following approaches:

- system component dependency analysis, component system matrix, component tree analysis or design structure matrix approach, see, e.g., Browning (2001)
- system functional analysis or function tree analysis (see for an example of diagrams used the automotive functional analysis presented in Campean et al., 2011)
- hazard list and hazard analyses like PHA, SSHA, SHA, O&SHA, see, e.g., Dixon (2018)
- variations of FMEA like FMECA, FMEDA, see, e.g., Carlson (2012)
- double failure matrix (DFM), see, e.g., Vesely et al. (1987).

The idea is to support each step of the resilience quantification and improvement cycle of Figure 1 with suitable tabular and matrix assessments. See Häring et al. (2017) and Häring and Gelhausen (2018) for further details.

For an efficient and consistent approach, the tables and entries should be designed such that they obey the following generic principles while resorting as far as possible to classical approaches to take advantage of best practice communities and experiences:

- Minimum and sufficient set of tables.
- Coverage of all main objectives of all steps of the resilience management cycle (see Figure 1).
- Avoidance of duplication of information (single point of information entry for each type of information).
- Explication of dependencies between tabular entries.
- Careful selection of level of abstraction.
- Iteration until convergence, leaving no open issues, e.g.,
  - a assignment of improvement measures to all disruptions evaluated as critical
  - b consideration of secondary effects of improvement measures

c consideration of overall effect of improvement measures as modified boundary and initial conditions.

- Taking advantage of all resilience dimensions.

Examples for dependencies that should be made explicit include the relations between overall objectives and stakeholders, critical infrastructure functions (services) and related subsystems and components, system functions and disruptions, and disruption events and potential counter measures.

The following list of tables and implied procedural scheme covers the key requests of the resilience quantification and management cycle of Figure 1 and most of the generic principles listed above:

1 Tabular system element analysis: e.g., system, subsystems, components, interfaces, object flows.

2 Tabular system function (service) analysis: e.g., system (non) performance functions, subsystem functions and related indicators.

3 Matrix analysis of dependencies of system functions on system elements, e.g., system (non) performance functions on subsystems and components. The matrix (correlation) analysis is achieved by combining two tables of 1 and 2.

4 Threat and disruption analysis: types of hazards, triggers, immediate effects, typical examples for system effects, frequencies and probabilities regarding occurrence, detection, avoidance mechanisms, respectively.

5 Preparatory matrix analysis of system elements with respect to potential disruptions, e.g., determine all disruptions that critically affect the system, subsystem and/or components.

6 Matrix analysis of system functions with respect to potential disruptions, e.g., determine all disruptions that critically affect any system (non) performance function or system sub function.

7 Tabular evaluation of each critical combination of system function and disruption, e.g., decide whether in the given socio-economic and decision-making context improvement measures are necessary and which types of improvements are possible.

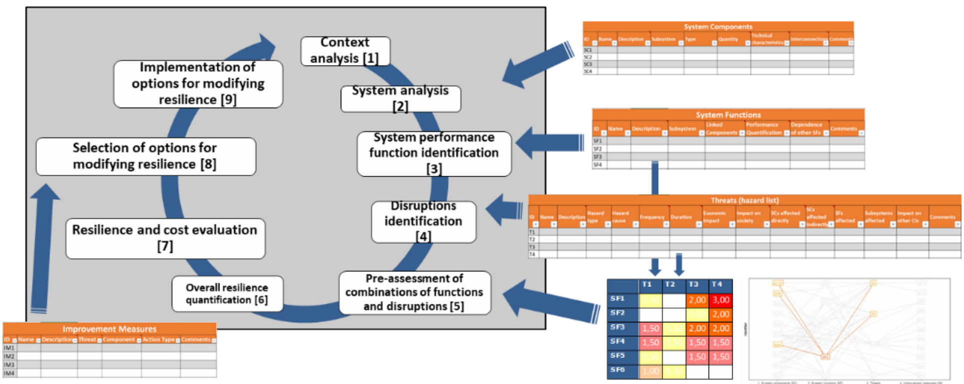
8 Tabular evaluation and selection of potential system development and optimisation options to address the critical combinations, e.g., assessment of options with respect to the overall risk reduction and resilience gain achieved per resources expended.

9 Tabular assessment of progress of each development step, system improvement steps and operational phases of the respective improvement options, e.g., using respectively system development processes, system update processes and system operational schemes.

10 Tabular assessment of progress of overall resilience quantification and improvement process, e.g., using self-assessment of the levels of completion, coverage, consistency and uncertainty of the resilience management steps.

Figure 10 gives an impression how such a set of tables could look like in the case of telecommunication infrastructure. It is shown how selected tables cover respective phases of the overall resilience quantification and improvement scheme. To this end, see for instance step 1 for system analysis '[2]' in Figure 10; 2 and 3 for system performance function identification '[3]', 5 for disruption identification '[4]' and 8 for selection of options for modifying resilience '[8]'. The deduced matrix and the evaluation of critical combinations 6 and 7 provides input for pre-assessment of combinations of functions and disruptions in '[5]'. In a similar way, other tables can be defined to support the 9-step process of Figure 9 and similarly of Figure 1.

Figure 10 Semi-quantitative tabular and matrix assessments for resilience quantification, optimisation and development (see online version for colours)



The approach presented in Section 6 is currently developed and applied within the EU project RESISTO, which assesses and improves the physical and cyber security of telecommunication infrastructure (RESISTO, 2019). The aim is to cover and improve the risk control and resilience with respect to all types of physical and cyber-attacks including also joint and coordinated attacks.

First feedbacks of practitioners hint at the need to reduce the tables and matrices to be used to a bare consistent minimum as far as possible. This concerns the number of tables and correlation analyses as well as the number of columns used within the tables.

As an example for a typical expression let $\{F_i\}_{1\leq l\leq N_{PF}}$ be a set of system (service) (non) performance functions, and $\{T_j\}_{1\leq j\leq N_T}$ be a set of threats and disruptions. Then

$$\begin{aligned} R_{ij} &= R\left(F_i, T_j\right), \\ M_{ijn} &= M_n\left(F_i, T_j\right) \end{aligned} \tag{7}$$

are a risk score for the criticality of the combination of the system (non) performance function and a threat or disruption and a mitigation measure deemed appropriate, respectively. In general, there are $\{M_{ijn}\}_{1\leq n\leq N_{ij}}$ mitigation measures. In a similar way, the other matrices are constructed with the help of the table entries.

Regarding quantitative simulative approaches of telecommunication grids, the tabular collection of system components, subsystems and overall system designs as well as the main system functions can serve as a valuable input for model design. Such approaches need furthermore in comparison to the model described in equation (5) to consider the communication protocols, which typically ensure that communication is feasible as long as only a single connection is available, even if the overall physical connection is much longer as the shortest connection without any disruption. In this sense, by their very design, telecommunication (internet) communication have built in resilience, corresponding to the fact the structures similar to the internet were designed for mitigating the effect of communications system parts.

7 Comparative conclusions and future topics

In summary, the current work presented and shortly discussed five different approaches to achieve overall risk and resilience assessment and quantification to improve risk control and resilience enhancement, see the first column of Table 1. Each of them used different overall processes to improve resilience of socio-technical systems, see the second column.

The comparison shows that all presented approaches allow moving towards system (non) performance function based risk and resilience approaches. This holds from single to multiple event-based overall risk control approaches, as best applicable to well localisable (with respect to space and/or time) potential events (e.g., intentional damage events or earthquake), via grid disruption insertion based simulation approaches, as best applicable to any (coupled) supply grids, to semi-quantitative and qualitative process-based adaptive scoring and tabular approaches as both best applicable for fast and efficient risk and resilience assessment of organisations, companies and critical infrastructure considered as socio-technical systems, in particular to identify the need for thorough risk and resilience quantification.

Again inspecting Table 1, it provides a detailed comparison of the five application examples of section 2 to 6: processes used (column 2), resilience cycle phases covered (column 3), technical resilience capabilities enhanced (column 4), and respective methods used (column 5) to achieve overall risk control and reduction for each representative approach (column 1). It is documented that each approach, independent of the actual methods used, covers all resilience cycle phases up to and including event occurrence. More post event assessment is mainly provided by the last four approaches (see column 4). Regarding enhancement of technical system resilience capabilities, mainly the situation modelling, assessment and decision making are covered (see column 5).

The level of a genuine systemic approach differs; see the second column of Table 1. Whereas the event and multiple event based risk and resilience approaches (see the first three approaches, rows 2 to 5 of Table 1) work with rather implicit system definitions (e.g., in terms of restricted scenario building and modification options allowed), in contrast in the cases of more system analysis and system performance function based approaches, the definition of the system itself is key part of the analysis itself (see the last two approaches, rows 5 and 6 of Table 1).Failure insertion approaches are by itself a well-established test strategy that can also be used for critical infrastructure assessment (see row 4 of Table 1). However, the resilience quantities that are determined using such an approach and in particular how they are evaluated are not. Also, the more recent resilience concepts such as performance-based resilience quantification and technical resilience capabilities are not novel by now anymore. However, how to use them for real operator needs remain challenging; see columns 3 and 4 of Table 1. Furthermore, it is important to select appropriate methods for efficient implementation of the approaches, see column 5 of Table 1.

Table 1 Comparison of application examples: processes, resilience cycle phases covered, technical resilience capabilities enhanced and respective methods used to achieve overall risk control and reduction

Approach and sample system (non) performance functions	*Processes (schemes) used for overall risk control and resilience enhancement*	*Resilience cycle phases covered (Logic phases, timeline-steps before, during and after events)*	*Technical resilience capabilities mainly enhanced*	*Main methods used within process*
Risk and resilience analysis and management of explosive events: time-dependent local and non-local, individual and collective risks of injury, damage or being out of service	Risk and resilience analysis for single (up to sets) of events (e.g., attack vectors). See Section 2	Preparation for representative events; analysis and improvement of protection and prevention (physical and organisational); absorption and initial damage analysis; what-if assessments analyses of response and stabilisation; recovery; adaption, learning and improvement	Representation of system, modelling and simulation of system; support of human decision making through the assessment of improvement options considering representative threat events	Historical-statistical analysis; engineering approaches; physical-simulative approaches for fragments; hydro code for complex blast; risk criteria (e.g., individual, FN criteria)
Susceptibility, vulnerability, averaged risk and rebuilding resilience quantification and management applicable to (sets of) potential event types with unknown location and event times; Adopted (non) performance functions as above for unknown events; Performance functions for response and recover behaviour	Consideration of multiple different terroristic events and event types at potential locations within risk and resilience analysis scheme; use of averaging quantities in terms of local event frequencies; Monte Carlo approach with representative events weighted with their relative or absolute probability; See Section 3	Preparation for potential terroristic events; analysis and improvement of (built) protection; analysis and improvement of prevention, e.g., access control, organisational, physical; absorption (vulnerability) analyses; analyses of response and stabilisation, recovery, adaption, learning and improvement options	Modelling and simulation of multiple potential events; support of decision making by identification of susceptible, vulnerable, high average risk, high-rebuilding time or cost areas, building and infrastructure parts	As above; in addition: statistical event analysis and combination; geo spatial and visualisation technologies; recovery modelling expert assessments
Coupled electricity grid, water and telecommunication grid agent-supported robustness and mitigation measure assessment: level of (non) service of grids on local and overall scale, e.g., availability of supply, level of supply and redundancy at nodes	Graphical, engineering or physical-simulative modelling and simulation of supply grids; (software) agents for physical-technical coupling; (operator) steering; agents for households, big consumers, producers (sources), and prosumers; failure insertion and disruption propagation for assessment of local and system wide effects; determination of averaging quantities; see Section 4	Preparation; analysis of levels of protection, prevention, initial damage effects; post event system behaviour regarding stabilisation, slow or fast recovery, or even improvement of system; possible systematic assessment of order of failures, of grid types affected, of level of dependency and of overall system failure	Modelling and simulation of infrastructure systems; support of decision making up to automated decision making regarding the best response in case of failures or disruptions; steering of actors in principle feasible in case of limited control	Graphical, engineering and physical grid simulations; coupling modelling of infrastructure grids; GIS layer visualisation of different infrastructure grids and nodes; visualisation of losses and cascades; feasible are behavioural models of all types of humans modelled

Table 1 Comparison of application examples: processes, resilience cycle phases covered, technical resilience capabilities enhanced and respective methods used to achieve overall risk control and reduction (continued)

Approach and sample system (non) performance functions	*Processes (schemes) used for overall risk control and resilience enhancement*	*Resilience cycle phases covered (Logic phases, timeline-steps before, during and after events)*	*Technical resilience capabilities mainly enhanced*	*Main methods used within process*
Semi-quantitative questionnaire based self-assessment and scoring of critical infrastructure systems: top-level critical infrastructure service functions and related key non-performance indicators, also in terms of relative semi-quantitative scales	Approach based on self-assessment and scoring of knowledge of infrastructure design, inter and interdependencies (on all systemic levels of abstraction as deemed relevant by analysts); of potential threats and disruptions and their effects within the complete resilience response cycle, in particular of improvement and counter measures; see Section 5	Mainly preparation and identification of more in-depth analyses; covers by definition and design all resilience cycle phases and relevant resilience dimensions; can be used to identify critical issues that require further assessment, including potentially quantitative assessments	By definition, resilience abilities and to a lesser degree technical resilience capabilities should be covered; technical resilience capabilities can be used as guidance for the assessment of the level of technical support of overall risk control and resilience enhancement management	Expert rounds and documentation; structured interviews; expert opinion gathering and analysis; user, citizen and decision maker involvement techniques; participative system development techniques; approach can resort to any detailed methodologies for solving specific analysis requests for which scores are determined
Tabular supply grid assessment of risk and resilience of telecommunication grids: (non) performance functions include being (not) connected, latency time level, throughput of data and level of (in)security of data	Coupled tabular approach which implements a system performance-based resilience semi-quantification, evaluation and improvement process; see Section 6	Time-dependent system (non) performance functions cover and can be used to assess all resilience cycle phases as deemed relevant for the system context; resilience cycle phases can be used to determine potential threats and disruptions of system performance functions, including post disruptions	Determination of critical combinations of system (non) performance functions and potential threats is key for a comprehensive modelling and simulation of systems; in particular to identify lacking technical resilience capabilities	Tabular system analysis approaches for inductive and matrix (correlation, causal) analyses; all types of methods for expert, stakeholder, users and third-party involvement, opinion gathering and evaluation; results of (quantitative) in-depth methods can be aggregated in tables for comprehensive assessment

More generally, the broad spectrum of processes followed and methods selected and discussed within this paper shows that there is no single best solution to resilience assessment and quantification: it depends on the context and available resources. Nevertheless, a trend towards more well defined quantitative-simulative and data driven approaches has been adopted by the presented approaches, including the systematic use of expert data.

The genuine quantitative approaches (see rows 2 to 4) should be strongly supported and typically be only conducted after preceding consistent, comprehensive, tailorable and flexible conceptual, qualitative and semi-quantitative approaches (see the rows 5 and 6 as examples) that help to identify in early assessment phases the key issues that need to be further covered and resolved by advanced quantitative approaches. Due to the still high resources and high level of quality of data needed, it is important to strongly focus on better quantitative assessments of real systems including an increasing leverage of sensor and monitoring data.

Finally, some outlook on future research activities is provided. On a long term and high ambition level, this includes the aim to provide the level ground for more unified semantic geospatial and semantic digital models of the built environment of infrastructure elements of grids of an ever increasing number of interconnected supply grid domains. This would take up parts of the future resilience research challenges and options as jointly collected in Xie et al. (2018a, 2018b), Mufti et al. (2018) and Yoda et al. (2018).

The aim is to enable a flexible ‘click, build and connect’ environment where single disruption events as well as multiple potential events (attack vectors) can be assessed on local as well as on interconnected grid levels on a predictive engineering level to quantify risk and resilience as well as to select most efficient counter and improvement measures. The ambition could be to resort to standardised digital system element models as far as possible and to extend them as appropriate, e.g., semantic CityGML, BIM and open source GIS digital models.

As being relevant for such more medium and long-term ambitions, some recently started projects are named along with their main goals. The German BMBF founded project SUSQRA (2019) characterises potential home-made explosive sources relevant for civil security contexts with the aim to provide better assessments, risk control and resilience enhancement regarding future potential attack scenarios. The BMBF project Urban Security 3D (2019) will determine critical urban spaces and areas regarding e.g., brightness, visibility, oversight and audibility using digital urban semantic city data. This is intended to be used for participative discussion of urban civil security issues and their mainly urban spatial and architectural improvement.

The BMBF project OCTIKT (2019) will show how to use organic computing approaches for steering systems of decentralised non-hierarchical smart electrical power supply grids on urban quarter level. Such systems consist of consumers, producers, storing systems and prosumers of different scales. The aim is to show how to use mainly locally available information sufficient for local modelling and simulation-based subsystem steering. The local steering should be sufficient for overall system high availability, risk control and resilience with respect to minor and major failures as well as disruptions of electrical distribution grid nodes and edges.

Acknowledgements

The first author wants to thank Xilin Lu (Research Institute of Structural Engineering and Disaster Reduction, Tongji University, Shanghai), Mohammad Noori (California Polytechnic State University, San Luis Opispo), Zhishen Wu (Department of Urban and Civil Engineering, Ibaraki University), Jian Zhang (International Institute for Urban Systems Engineering, Southeast University, Nanjing), Ying Zhou (International Joint Research Laboratory of Earthquake Engineering, Tongji University, Shanghai) and Gian Paolo Cimellaro (Department of Structural, Geotechnical and Building Engineering (DISEG), Politecnico di Torino) for the inspiring second International Workshop on Resilience (IWR 2018) at Southeast University Nanjing and Tongji University Shanghai. The research discussed in this publication hast partially been supported by the EU Security research Grants for VITRUV (EU Project ID: 261741), ENCOUNTER (EU Project ID: 285505), D-BOX (EU Project ID: 284996) and EDEN (EU Project ID: 313077). Also by the projects SNOWBALL (EU Project ID: 606742), BESECURE (EU Project ID: 285222), RESILENS (EU Project ID: 653260), and RESISTO (EU Project ID: 786409).

The sorting of the main body of authors is with respect to their contributions to the flow of the content of Sections 2 to 6.

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