ARTICLE IN PRESS
TFS-18790; No of Pages 20
Technological Forecasting & Social Change xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Technological Forecasting & Social Change

A spatial-temporal vulnerability assessment to support the building of community resilience against power outage impacts

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ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 30 September 2016
Accepted 30 November 2016
Available online xxxx

Keywords:
Decision making
Spatial-temporal vulnerability assessment
Monte-Carlo simulation
Delphi survey
Community resilience building
Power outages

ABSTRACT

Power outages are among the most serious Critical Infrastructure (CI) disruptions and require effective disaster management with collaboration of affected CI providers and disaster management authorities. To support building community resilience, we introduce a vulnerability assessment which allows an enhanced spatial-temporal understanding of initial power outage impacts. Using the assessment enables planers to better identify which and when CIs become vulnerable and how important they are in comparison to other CIs before the overall crisis situation escalates and unmanageable cascading effects occur. The assessment addresses the initial phase of a power outage and corresponding early measures of local risk and crisis management organizations according to the German disaster management system. The assessment is an indicator-based approach which is extended to consider time-depending effects through time-referenced demand and the depletion of Coping Capacity Resources (CCR). The estimation of the relevance of CIs regarding the provision of vital services and products is addressed by a modified Delphi method. In addition, an expert survey was conducted to shed light on the evaluation of coping resources. In this paper, we describe the components of the assessment and propose different aggregation approaches which each enhances the understanding of spatial-temporal impacts of a power outage, and, hence, increases the forecasting capability for disaster management authorities. For demonstration purposes, the assessment is implemented for the case of the city of Mannheim, Germany.

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1. Introduction

Within the Energiewende, the German electricity system is experiencing a historic turnaround towards a more sustainable, more efficient, and smarter energy system, including renewable and low-carbon energy generation. However, the change also implies new and unknown risks. As a consequence, the risks accompanying power outages became an even more important issue in disaster planning. For disaster management, the electric power grid is already the most "critical" infrastructure, since all Critical Infrastructures (CIs) (e.g. hospitals, pharmacies, General Practitioners (GP), etc.) depend on a reliable electricity supply (see, e.g., der Vleuten and Lagendijk, 2010; Kröger, 2008; Luiijf et al., 2009; Pescaroli and Alexander, 2016).

According to the Sendai Framework, the United Nation (UN) emphasizes the strategic target to reduce disruptions of basic services and to strengthen the resilience of communities (UNISDR, 2015). Making communities more resilient against the impacts of power outages means to increase "the ability […] to resist, absorb, accommodate to and recover from the effects […] in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions" (UNISDR, 2009). In the present paper, the theory of vulnerability is a theoretical concept that is used as a functional measure instrument to enhance resilience. Vulnerability expresses the degree a region or CI can be affected by a power outage. It is a measure of the CI service losses due to a power outage taking into account criticality and resilience of (potentially) exposed CIs.

In order to measure and enhance community resilience against power outage impacts, several substantial challenges have to be faced. The following list is a non-concluding enumeration of the challenges that will be discussed in the following sections in detail:

- Disaster management authorities have to plan for the accompanying risks of missing CI services taking into account spatial-temporal characteristics of power outage exposed CIs and citizens. Therefore, planning tools are required, which in particular allow analyzing the impacts on local level.
- Each CI provider is responsible for its own disaster preparation. However, an effective disaster management planning can only be ensured by a joint collaboration between CI providers and the responsible disaster management authorities. Effective planning is based on a harmonized and well-arranged coping approach. The problems here are the heterogeneous interests of CI providers and

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http://dx.doi.org/10.1016/j.techfore.2016.11.027
0040-1625/© 2016 Published by Elsevier Inc.

Please cite this article as: Münzberg, T., et al., A spatial-temporal vulnerability assessment to support the building of community resilience against power outage impacts, Technol. Forecast. Soc. Change (2016), http://dx.doi.org/10.1016/j.techfore.2016.11.027

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disaster management authorities which results in a missing comparability of impacts. This makes it difficult to generate a common understanding of the potential local power outage consequences for a comprehensive decision base that is acceptable by all stakeholders.
- The vast majority of power outages last for a maximum of several hours. Already in such short disruption periods the consequences can be severe in particular with regard to the provision of CI services. The underlying danger is within interdependencies between the CIs which allow propagation of failures into other CI systems (domino ad cascading effects). Therefore, it is essential to understand the initial impacts on CIs, to identify which and when CIs become vulnerable, which amount of CI service lost has to be avoided and how important the individual CIs are in comparison to other CIs before the overall crisis situation escalates. The vulnerability paths have to be identified and, as far as possible and appropriate, be managed before uncontrollable cascading effects arise.
- The decisive point of leverage for building community resilience is the management of the initial and direct effects on CIs, although resilience comprises of preparing, adsorbing, and recovering from adverse consequences of a power outage. In addition, the initial and direct effects imply immediate sufferings that require instantaneous attention. The management of these impacts provide the most prompt effective and feasible basis to build resilience.

To facilitate the enhancement of community resilience, we propose a spatial-temporal vulnerability assessment. The vulnerability assessment should allow an improved disaster risk governance by providing a better understanding of the initial impacts of a power outage taking into account the individual characteristics of CIs. The assessment aims at estimating the reduction or loss of CI services in a certain city or county under the impacts of a power outage. To this end, the assessment allows for a systematic and structured evaluation of the exposure of people and CIs, their coping capacities, and their criticality in discrete time steps. On this basis, time-depending effects can be assessed, vulnerability paths can be identified, and determined forecasting is possible. The assessment results should foster investments for mitigating and minimizing disaster risks triggered by power outages and strengthen the collaboration between CI providers and disaster management authorities.

The assessment is based on a multi-indicator approach. A Delphi survey and decision maker evaluations are conducted to define weights and parameter values. The spatial-temporal vulnerabilities of districts and CIs are determined by aggregation taking into account the characteristics of the affected CIs. Specific attributes of a present or potential power outage scenario can be considered.

This paper is structured as follows: The abovementioned challenges for enhancing community resilience in the context of power outages are discussed in the second section. In the third section we briefly present the current state of the research in simulating power outage impacts. In the fourth section, we introduce the development of the spatial-temporal vulnerability assessment. In the fifth section, the introduced assessment is applied to an exemplary case. The use case and its results are described and discussed. Furthermore, a sensitivity analysis of varying weighting values is conducted and the outcome of different coping strategies are calculated to demonstrate the benefits of the assessment. The paper closes with critical remarks and a conclusion in the last section.

2. Challenges in enhancing community resilience

The core challenges for enhancing community resilience are already enumerated in Section 1. However, it is necessary to provide a comprehensive overview about the underlying problems, decision makers, and decision situations. To do so, the disaster management planning and the collaboration between CI providers and disaster management authorities are discussed in detail from a practical perspective in this section.

2.1. Disaster management of power outage impacts

As the German disaster management system is organized in a federal manner, each of the more than 400 local disaster management authorities has to manage the impacts of a power outage in the region for which they are in charge. Following the German incident command system (SKK, 1999), a crisis management group for major incidents is established in each city or county to manage any kind of disaster. Each crisis management group consists of the administrative crisis management team ("Verwaltungsstab") and an operational crisis management team ("Führungsstab"). The group members come from the local fire brigade, the local administrative departments, and the disaster management authority. There are also special advisers ("Fachberater") who represent aid organizations and CI providers, for instance. In the remainder of this paper, we always understand the members of the crisis management group as decision makers and end users of the assessment results.

According to the planning for power outages, the decision makers' focus lies on the upcoming situation of a disaster (Ryan, 2013). In particular CIs services should be kept continuous to the greatest possible extent. The longer a disruption lasts and the more important and vulnerable the exposed CIs are, the more probable are life-threatening risks. The general life-threatening impacts are well-known and many publications cover the causal relation (see, e.g., Hiete et al., 2010; Petermann et al., 2010; Klinger et al., 2014; Berariu et al., 2015; Castillo, 2014; Barata et al., 2005; Nakayama et al., 2014; Wong et al., 2007; Zubin et al., 2007). However, academic research which establishes the link between electricity supply and resilience is still seen as insufficient (Kinn and Abbott, 2014). The information about potential escalations is often vague, generic, and does not take into account the unique specifications of a certain city or county. The requested decisive information for disaster planning is about which and when a CI becomes vulnerable and how important an individual CI is in comparison to other CIs during a power outage. The current foresight capacity of the disaster management authorities is often not sufficient to predict the concrete spatial-temporal impacts in the way required for an effective disaster risk management and contingency planning.

The spatial-temporal impacts in turn depend on the individual characteristics of a CI. The CIs have different Coping Capacity Resources (CCR) whereby the ability to absorb the adverse effects and to maintain a vital supply for the population during a power outage varies. In addition, the CIs differ in its importance for the population. The importance depends on the CI's services and products, the size of the CI, and the daytime of the power outage. As a consequence, the CIs do not suffer in the same way and at the same time. To ensure a comparability, the specific character of each CI has to be put into relation with the characteristics of other CIs.

The knowledge about how a power outage escalates and the comparability of exposed CIs can enhance the resilience in different ways. In general, it is not possible to determine the point in time at which the situation suddenly becomes life-threatening. Being aware of this tipping point is very important in disaster planning, because until this point the affected CI provider and population may rely on their own self-helping capacity without any additional assistance from emergency and disaster management units. Furthermore, it is essential to have spatial-temporal information about the impacts to ensure an appropriate and proper intervention (Ryan, 2013; Quarantelli, 1997). By this knowledge, weak and vulnerable CIs can be identified and the corresponding CI provider can be motivated to invest more in CCRs. During a power outage, the disaster management authorities can concentrate their activities to the CIs which have higher vulnerability values or are more important for the population as other CIs. During a present power outage, knowing the tipping point enables warnings and further preparations which may lead to a better resistance. Sometimes the disaster management

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