Resilience Analysis of Urban Critical Infrastructure:
A human-Centred View of Resilience

Kazuo Furuta[i]* and Taro Kanno[i]

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*Corresponding author: furuta@rerc.t.u-tokyo.ac.jp

Introduction

The Great East Japan Earthquake and the disaster at Fukushima-Daiichi Nuclear Power Plant in 2011 were events that caused many people to attend to resilience in Japan. After the disaster in 2011, the National Resilience Promotion Office was established in the Cabinet Office in 2013, and the Basic Act for National Resilience (Cabinet Secretariat, 2013) was enacted in the same year. Following the Basic Act for National Resilience, the Fundamental Plans for National Resilience both for the central government and for local governments were established and will be revised periodically. People have recognized that more comprehensive approaches than the conventional ones for disaster prevention are required in order to be prepared for unanticipated situations, like those experienced in 2011. In particular, resilience of urban critical infrastructure is a critical issue for saving lives in a crisis.

After the Great East Japan Earthquake, industry and civic life were severely disrupted not only in the damaged area of Tohoku district but also in the metropolitan area of Tokyo. Many power generating plants were damaged, causing shut down, and a planned blackout was enforced in the metropolitan area of Tokyo, lasting for about a week. In the damaged area of Tohoku district, it took more than a month to recover the lifelines and recovery of local communities is still under way.

Resilience has been defined and used as a technical term in various areas, but from a viewpoint of systems safety it stands for capabilities of a socio-technical system to absorb internal as well as external threats and to maintain its functionality (Hollnagel, Woods, & Leveson, 2006). It is a concept derived following great efforts around how to attain the safety of complex socio-technical systems that consist of hardware, human, organizational components, and interactions between them.

Risk-based and resilience-based safety design

In the conventional approach of safety design, the system is designed to achieve some design basis derived from a particular presumed threat scenario. The design basis is determined so that the risk that the actual system status may go beyond the design basis and then cause losses to the society will be kept below the allowable limit. It is assumed that the risk can be evaluated empirically as a

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[i] School of Engineering, The University of Tokyo

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combination of the scale and the probability of expected losses. The residual risk below the allowable limit is often neglected and retained in the system.

Resilience sheds light to this residual risk neglected in the risk-based approach of safety design, and it can be seen as an extension of the risk-based approach. Resilience therefore complements rather than replaces the risk-based approach. Resilience includes not only the preventive measures of disaster but also the responses to unfavourable outcomes of disaster. The recovery speed of system functionality is therefore discussed very often in the resilience literature and the resilience triangle is a useful measure for quantitatively representing the degree of system resilience.

The recovery speed, however, is not the only measure that is relevant to resilience. Recovery cost, for instance, is sometimes considered in the assessment of system resilience. In our study on the resilience of urban critical infrastructure, the amount of recovery efforts is used in addition to the recovery speed as a resilience measure. In the Infrastructure Resilience Analysis Methodology (Biringer, Vugrin, & Warren, 2013), the resilience measure is composed of Targeted System Performance (TSP), System Impact (SI), and Total Recovery Effort (TRE). We adopted this methodology for assessing the resilience of a telecommunication network after disaster. In this assessment, we defined TSP as the design capacity of the telecommunication lines without any damage, SI as the degradation from TSP represented as the call loss rate, and TRE as the social utility loss caused by traffic regulation.

Other system characteristics are also useful for quantitatively representing the system resilience. We adopted the R4 framework of resilience, where resilience is represented in terms of four aspects of robustness, redundancy, resourcefulness, and rapidity (Bruneau, et al., 2003), in the sensitivity analysis for model validation. Which measures are useful depends on the purpose of analysis.

Human-centred view of resilience

When discussing the resilience of critical infrastructure, recovery of hardware facilities and components are focussed on from the standpoint of infrastructure operators. We should, however, focus more on the standpoint of end users. Resilience for whom is a key question to be asked, and recovery of civic life that depends on critical infrastructure should be the final goal. Since civic life is the basis that provides workers of the infrastructure industry, infrastructure operation and its recovery heavily depend on the civic life system.

Civic life also depends on various industries and services other than infrastructure business. Medical, financial, and administrative services are, in particular, of critical importance after disaster. These industries and businesses are interconnected through a supply chain or a service chain and these chains depend on the operation of infrastructure. It is remarkable that some industries were halted due to disrupted supply chains after the Great East Japan Earthquake and the flooding in Thailand in 2011, though the industry locations were removed from the areas of damage. Industries depend in turn on civic life, because people cannot join the workforce if their living conditions have not been recovered.

In order to analyze the resilience of urban critical infrastructure in reality, it is necessary to consider not only the lifeline hardware subsystem but also the service subsystem and the civic life subsystem for introducing a human-centred view. There are multiple interdependencies between these three subsystems, and they form a very complex system of systems as shown in Figure 1. Additionally, in our evaluation model of critical infrastructure resilience (Kanno & Furuta, 2012), the objective function for recovery planning includes not only the recovery level of lifeline capacity but also the recovery level of service activities and the satisfaction level of citizens. The satisfaction level of citizens is evaluated by scoring the everyday activities that are possible under the recovery condition of lifeline and services. The recovery cost, which is measured by the travel distance of recovery teams and the time required for recovery, is also minimized in recovery planning. The tasks for providing service and repairing damaged infrastructure are modelled by the PCANS model (Krackhardt & Carley, 1998). The supply chains among the agents in the service subsystem are also considered. This framework enables us to assess the resilience of critical infrastructure considering the above-mentioned human-centred view.

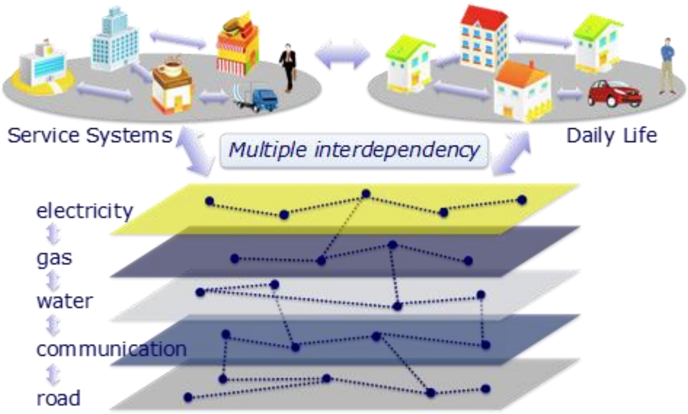

Figure 1: Model of multiple lifeline systems

In some cases, stakeholders of different characteristics have to be distinguished in greater detail. Since people of different characteristics will have different senses of value, the same system in the same situation may have different value for them. This issue was demonstrated by a trial evaluation of the resilience triangle of lifelines after the Great East Japan Earthquake using the Maslow hierarchical model of human needs and the persona method (Furuta, 2014). In this trial, the resilience triangle was evaluated for three personas of different characteristics living at the same location and it was shown that the satisfaction levels of physiological, safety, and social needs differ. This is because, for example, recovery of healthcare service is more critical for physiological needs of an elder person with a health problem than a young person of a working age. On the other hand, recovery of the public transportation is important for social (economic) needs of a young person who is commuting to his/her working place.

This issue may cause conflicts of interest between different stakeholders and become a downside of resilience. Consensus should therefore be formed by compromising the conflicting interests, though this would not be a trivial process. Since it is not an issue just with resilience but also with the risk-based approach, we need some effective method for fair as well as rational social decision-making.

Resilience analysis of critical infrastructure in Tokyo

We have developed a simulation system for resilience analysis of urban critical infrastructure based on the comprehensive framework shown in Figure 1. The lifeline, service, and civic life subsystem are represented as interdependent coupled networks (Buldyrev, et al., 2010) and agent-based models.

The recovery plan of damaged lifelines can be optimized by the genetic algorithm (GA) by minimizing the resilience triangle of the hybrid objective function already explained. We have also developed a model of critical infrastructure in the central 23-ward area of Tokyo with a 30x30 square grid (Kanno, Yoshida, Koike, & Furuta, 2018).

Resilience of urban critical infrastructure is evaluated as recovery curves of lifeline, service, and civic life subsystem obtained by the simulation. An example of an analysis result for a scenario of a Tokyo metropolitan epicentral earthquake is shown in Figure 2, where the recovery level of the lifeline, service, and civic life subsystem are shown in colour maps along the timeline of days after the event. The damage level of lifeline just after the earthquake depends heavily on the location of the epicentre and the predicted seismic intensity. It is suggested from the result that recovery of the downtown area, where the headquarter functions of the government and principal industries are concentrated, is prioritized so that the recovery plan can be optimized.

The proposed analysis method was useful for predicting the time- and space-dependent response of urban critical infrastructure after disaster and for evaluating its resilience. This analysis then can provide us with valuable insights for making proposals for improving the emergency response policy of both public and private organizations. The operation companies of the lifeline facilities can, for instance, identify bottlenecks in the lifeline subsystem and eliminate them by redesigning the lifeline facilities. The national and local governments can improve their disaster response plans such as the location of emergency supply bases.

Since the proposed model considers not only the lifeline subsystem but also the service and civic life subsystem, the analysis will also be useful for urban planning, so that the critical urban infrastructure, which is a complex system of systems, can be made resilient against threats of various types and adaptive under environmental and social transitions in the long term.

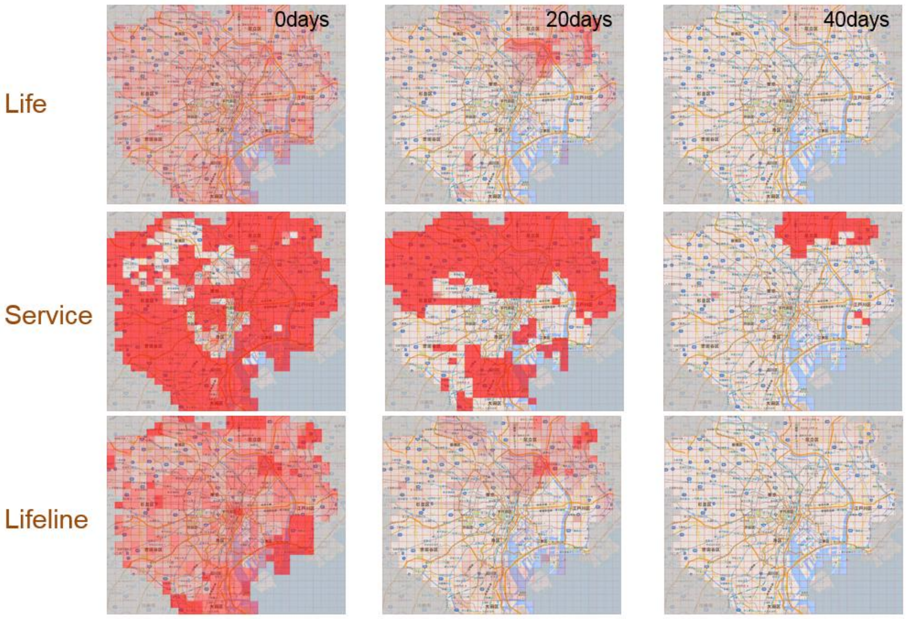

Figure 2: Resilience map of the 23-ward area after Tokyo metropolitan epicentral earthquake

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