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A Novel Critical Infrastructure Resilience Assessment Approach using Dynamic Bayesian Networks

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Abstract. The word resilience originally originates from the Latin word "resiliere", which means to "bounce back". The concept has been used in various fields, such as ecology, economics, psychology, and society, with different definitions. In the field of critical infrastructure, although some resilience metrics are proposed, they are totally different from each other, which are determined by the performances of the objects of evaluation. Here we bridge the gap by developing a universal critical infrastructure resilience metric from the perspective of reliability engineering. A dynamic Bayesian networks-based assessment approach is proposed to calculate the resilience value. A series, parallel and voting system is used to demonstrate the application of the developed resilience metric and assessment approach.

INTRODUCTION

The concept of resilience was firstly introduced in the field of ecology by Holling. He defined resilience as a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables [1]. To date, the concept of resilience has been spread from ecology to various fields, such as economics, psychology, and society. Compared with the research in these contexts, only a small proportion of resilience-related research exists in the field of critical infrastructure [2].

For critical infrastructure, some definitions are proposed depending on the objects of assessment. For example, the National Infrastructure Advisory Council defines critical infrastructure resilience as the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event. The American Society of Mechanical Engineers defines resilience as the ability of a system to sustain external and internal disruptions without discontinuity of performing the system's function or, if the function is disconnected, to fully recover the functions rapidly [3]. According to these definitions, various resilience metrics of and corresponding assessment approaches are developed. However, it is still challenging to quantify the resilience for a specific critical infrastructure, because of internal and external influencing factors involved in such metrics.

We aim to develop a universal critical infrastructure resilience metric from the essence and property of resilience of critical infrastructure. From the perspective of reliability engineering, steady-state availability and steady-state time

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can be used to represent the performance-related property and time-related property, respectively. Since each critical infrastructure has its availability, according to the steady-state availability and steady-state time, the resilience value can be obtained easily; therefore, the metric is suitable for each critical infrastructure. It provides an implement guidance for infrastructure planning, design, operation, construction, and management. In the current paper, a universal critical infrastructure resilience metric is developed and a dynamic Bayesian networks-based assessment approach is proposed to calculate the resilience value.

UNIVERSAL ENGINEERING RESILIENCE METRIC

Each critical infrastructure has its availability, it is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided. The availability of a critical infrastructure decreases continuously to reach a steady-state availability A_1 at steady-state t_1 from the initial time with the initial availability of 100%. This progress is caused by degradations of components and daily maintenance of this infrastructure. Suppose an external shock occurs at time t_2, the availability decreases to a post-shock transient-state availability A_2 instantaneously, and then increases to a new equilibrium state A_3. This progress is also caused by emergency repair after shock as well as degradations of components (See Figure 1).

The steady-state availability A_1, post-shock transient-state availability A_2, post-shock steady-state availability A_3, steady-state time t_1, and post-shock steady-state time (t_3-t_2) are totally determined by the structure of critical infrastructure and maintenance resource, for example, redundant structure, failure rate, repair rate, etc. High redundancy, low failure rate or high repair rate lead to high steady-state availability and short steady-state time before and after any shocks. This accords with the essence and property of resilience. Therefore, steady-state availability and low steady-state time are used to represent the performance-related property and time-related property of critical infrastructure resilience. Since steady-state availability and steady-state time are easy to obtain, it is no longer challenging to quantify the resilience with an appropriate resilience metric.

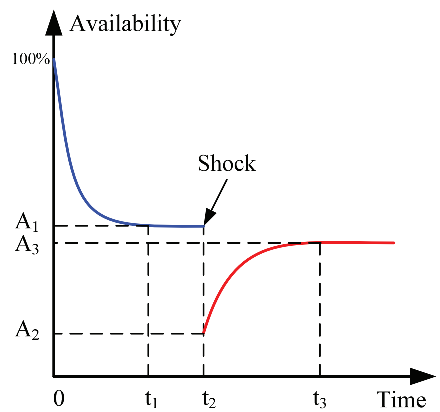

FIGURE 1. Availability of a system subject to degradation and shock.

The purpose that we propose the resilience metric is to compare the resilience of different systems that achieve same functions and hence identify different internal factors that contribute to it. We develop a universal resilience metric that incorporates performance-related properties and time-related properties using steady-state availability and steady-state time before and after external shocks as follows.

$$\rho = \frac{A_1}{n\ln(t_1)}\sum_{i=1}^{n}\frac{A_2^i A_3^i}{\ln(t_3^i - t_2^i)} \tag{1}$$

Because the external factors, such as disturbance, attack and disaster events, are random and unpredictable, we think they are not the influencing factors of resilience, and not involved in the resilience metric. The external factors are only the trigger of "bounce back". This is similar to the spring system, an external force *F* can extend or compress a spring by some distance *X*, and the spring can bounce back to initial balance once the force *F* is removed. According to the Hooke's law, the stiffness of the spring can be expressed as $k=F/X$. It is a constant factor characteristic of spring, determined by the spring itself, but not by the force. The defined resilience ρ is just like the *k*, but for the critical infrastructure, the external factors and responses of this infrastructure are not directly proportional relationship. Therefore, we determine a series of shocks on the critical infrastructure, which lead to common cause failure of components. The prior probability of common cause failure for each component is defined as

$$p_i = \frac{i}{n+1} \quad i \in [1,n] \tag{2}$$

Where *n* is the number of shocks. Generally, we select n=9 to evaluate a critical infrastructure resilience.

For different shocks, the repair rates of components are totally different with fixed maintenance resources. With a shock is serious, the maintenance resources are dispersed, causing low repair rates of components. For the sake of simplify, we defined the repair rate of component under different shocks as

$$\mu_i = (1 - p_i)\mu \tag{3}$$

Where μ is the repair rate of each component in normal circumstances.

Based on the prior probabilities of common cause failure and corresponding repair rates of components, the steady-state availability of the critical infrastructure can be obtained as follows.

$$A(\infty) = \lim_{t \to \infty} A(t) \tag{4}$$

It is noted that a real steady-state availability does not exit, in practice, we therefore defined a steady-state availability is the availability when the difference within five continuous time point (hour) is equal to or less than 10^{-5}, and the time is term as steady-state time. In this current work, we proposed a dynamic-Bayesian-networks-based assessment approach for steady-state availability, steady-state time and subsequent resilience.

SERIES, PARALLEL AND VOTING SYSTEM

Series, parallel and voting system is an abstract system, which is composed of three series components, three parallel components, and three voting components, denoted by S3P3V3 (See Figure 2a). The series subsystem works only when all of the three series components S1, S2, and S3 work; the parallel subsystem works when any one of the three components P1, P2, or P3 works; the 2-out-of-3 (2oo3) voting system works when at least 2 components of V1, V2, and V3 work. The entire system works only when all of the three subsystems work, is therefore equivalent to a series system. Many system in practical critical infrastructure can be abstracted as series, parallel or voting systems, hence this simple S3P3V3 system is a typical case for demonstrating the application of resilience metric in critical infrastructure.

We propose a dynamic-Bayesian-networks-based resilience assessment approach of critical infrastructure. The advantage with respect to a classical probabilistic temporal model like Markov chains is that the dynamic Bayesian networks are stochastic transition models factored over a number of random variables, over which a set of conditional dependency assumption is defined [4-6]. We adopt dynamic Bayesian networks to predict the future state of variables taking into consideration the observation of variables up to now. That is, we can predict the steady-state availability and steady-state time of a critical infrastructure based on the current state of components, such as external shocks destroy some components.

At a specific time slice of dynamic Bayesian networks of the S3P3V3 system (see Figure 2b), for example, Slice1: *t*, the components and their states are denoted by root nodes, including S1, S2, S3, P1, P2, P3, V1, V2 and V3. The transient availability of the entire system is denoted by the final leaf node, A. We artificially add some intermediate nodes, including S, P and V, to simplify the conditional probability table of related nodes. The causal relationships between the nodes are connected by intra slice arcs.

The dynamic Bayesian networks are essentially replications of static Bayesian networks over *n* time slices between *t* and $t+(n-1)\Delta t$. A set of inter arcs between adjacent time slices *t* and $t+\Delta t$ connect the corresponding nodes of components, representing the dynamic degradation process and daily maintenance or emergency repair of components. All the information required to predict a state at time $t+\Delta t$ is contained in the description at time *t*, and no information about earlier times is required, which means that the process has the Markov property.

Dynamic Bayesian networks parameter model is composed of intra slice parameter model and inter slice parameter model. For the intra slice parameter model, the marginal prior probabilities are assigned to them according to the resilience metric Eq. (2), and the conditional probability tables are determined using the series, parallel and voting relationship. For the inter slice parameter model, we use Markov state transition relationship to determine the dynamic degradation process and daily maintenance or emergency repair of components. With appropriate inference algorithms of dynamic Bayesian networks, either exact or approximate, we can predict the steady-state availability, steady-state time and final resilience value of this system.

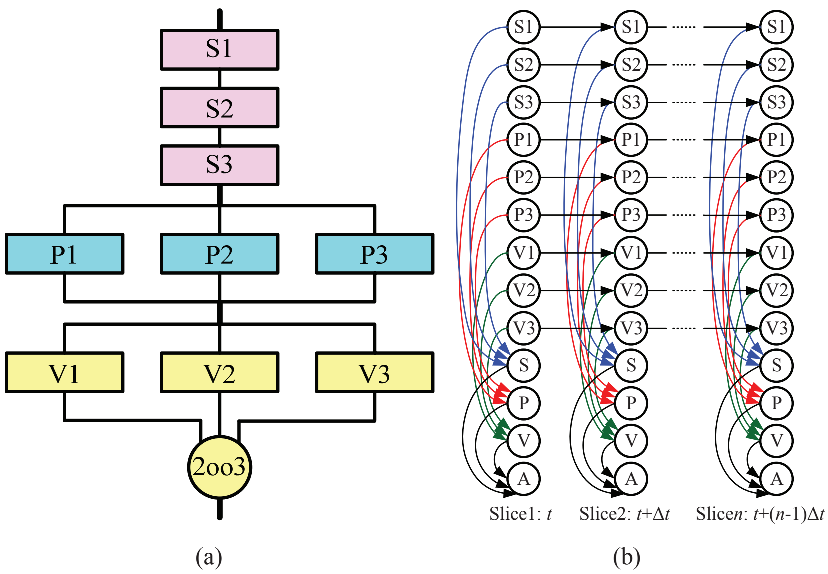

FIGURE 2. A simple system composed of series, parallel and voting subsystems and corresponding dynamic Bayesian networks.

The trends of availability without external shocks or with different external shocks are totally different (See Figure 3). When no shocks occur, that is, during normal running of the S3P3V3 system, the availability decreases rapidly from 100%, and reach a stable level 99.365% at the 15th hour. The steady-state availability and steady-state time are therefore 99.365% and 15, respectively. During emergency circumstances, the availabilities decreases to a minimum valve the moment the shocks occur, and subsequently increase to reach different stable levels. Taking AY1 as an example, the prior probability of 10% of common cause failure are assigned to each component at the original time, the availability decreases to 70.790% immediately, and with emergency repair, it increases rapidly, and reach the stale level 99.311% at the 27th hour. Hence, the post-shock transient-state availability, post-shock steady-state availability and post-shock steady-state time are 70.790%, 99.311%, and 27, respectively. We can see that with the increasing of probability of shocks, the post-shock transient-state availability and the post-shock steady-state availability decrease, and post-shock steady-state time increases. This is accorded with the fact. Using all the characteristic values, we obtain the resilience value of the S3P3V3 system of 1.90% with the proposed resilience metric.

Since the resilience is determined by the critical infrastructure itself but not external shocks, the factors that affect the performance of system, are certain to affect the resilience value. System structures, failure rates and repair rates of components are main influencing factors.

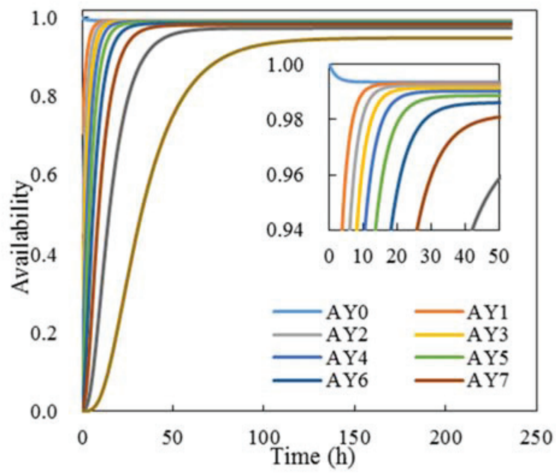

FIGURE 3. Availability of the S3P3V3 system subject to degradation and different shocks.

CONCLUSION

We develop a universal engineering resilience metric from the essence and property of resilience of engineering system. The metric is closely related to the steady-state availability and steady-state time, which represent the performance-related and time-related properties of a resilient system. Based on this metric, we develop a dynamic-Bayesian-networks-based resilience evaluation approach, and use a series, parallel and voting system to demonstrate the metric and corresponding approach. The results show that the proposed resilience metric and evaluation approach work well, and can be used to compare, optimize and design any engineering systems.

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