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Risk response for urban water supply network using case-based reasoning during a natural disaster

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ABSTRACT

Risk response is a pivotal part of critical infrastructure protection, especially in a natural disaster situation. Historical cases are deemed the most effective resources to support emergency decisionmaking on time-limited response strategy plan, but research on this issue is still relatively scarce. This paper uses the case-based reasoning (CBR) method to analyze the response to risks connected with urban water supply network (UWSN). It puts forward a pragmatic method considering the natural disaster situation. The innovation focuses on three key parts. Firstly, ontology model is employed to represent domain and response knowledge including disaster scenario features, UWSN risks and response strategies. Secondly, a two-step case retrieval method is used to match disaster scenarios in order to generate available case set and then obtain similar case set by risk matching. Thirdly, based on the differences between scenarios, inappropriate risk response strategies in the similar case set are adjusted in order to generate practical response strategy plan. Finally, an urban case study shows that the proposed method is capable of extending the CBR method to risk response in UWSN.

1. Introduction

Critical infrastructure (CI) such as urban water supply network (UWSN), electric power network, transportation network, etc. plays a more and more important role on urban development (Ouyang, 2014). It is generally considered as the related system that is essential to the fundamental operations of urban society, economy and government (Zhang et al., 2015a). As one of the most important CI systems, UWSN is interconnected and interdependent with other CI systems and the situation will be extremely complex, dynamic and uncertain when they are struck by natural disasters. Poor risk management in severe natural disaster situation will increase the likelihood of serious damage to UWSN system. For example, the 11th March 2011 eastern Japan earthquake triggered an enormous tsunami that caused blackouts and led to a widespread shortage of drinking water. In 2012 in hurricane Sandy, heavy rainstorm devastated a large area of North America, and flood, the secondary disaster, caused power plants and water plants to shut down. In such cases, researchers have put forward constructive suggestions and have used case studies to show countries' governments the positive results of protecting UWSN (Chérifa et al., 2012; Di Nardo et al., 2016, Di Nardo et al. (2013)). In general, urban emergency management personnel should focus UWSN protection on risk analysis and vulnerability reduction (Hellström, 2007), also the investment strategy with the highest consequences should be employed (White et al., 2014).

A typical risk management process mainly consists of four steps: risk identification, risk analysis, risk response and auditing and continuous improvement (Adar and Wuchner, 2005; Ariff et al., 2014; Buchan, 1994; Kwak and Stoddard, 2004). So far, many studies on CI protection mainly focus on risk identification and risk analysis by priority ranking (Bochkov et al., 2015; Zhang et al., 2015a), reliability analysis (Johansson et al., 2013), vulnerability analysis (Chatzipoulidis et al., 2015; Johansson et al., 2013; Marrone et al., 2013), cascading effects analysis (Chopra and Khanna, 2015; Utne et al., 2011), failure analysis (Pietrucha-Urbanik, 2015; Wu et al., 2013), etc. Moreover, auditing and continuous improvement has been paid attention related to CI protection by measuring effectiveness of previous risk management steps (Adar and Wuchner, 2005; NIPP, 2013; Yusta et al., 2011), and business continuity planning method has been employed for auditing and continuous improvement toward CI risk management (Sun et al., 2016; Sun and Li, 2014). However, how to generate more effective risk response strategy plan is less considered for CI protection, which has been widely discussed in project management (Fan et al., 2015; Zhang, 2016; Zhang and Fan, 2014). The main methods on risk response mainly adopt: (1) Optimization model such as integrated approach (Ben-David and Raz, 2001), Bayesian networks (Hu et al., 2013), and economic perspective

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programming with consideration of risk response effect (Zhang and Fan, 2014) and expected utility (Zhang, 2016); (2) Graph centrality analysis (Stergiopoulos et al., 2015) and (3) Logistic regression modeling (Restrepo et al., 2009). But most of the above principles presented are theoretical and difficult to implement in practice for UWSN risk response. For instance, optimization model is hard to quantify all the features (Fan et al., 2015) and also has some constraints to obtain the accurate results without errors in natural disaster situation. Graph centrality analysis and logistic regression modeling will be of little use in uncertain natural disaster situation with incomplete information. On the other hand, the composition of CI risk is quite complex, which is difficult to identify and list all the possible risks in current natural disaster situation. Therefore, an in-depth research on risk response should be strengthened to protect UWSN and its related CI systems in a stable condition.

Given the aforementioned limitations of the existing methods and the related studies (Lu et al., 2013; Wang and Boukamp, 2011), we can see that the traditional CI risk management is generally not only less flexible toward the changes of risk situation due to its time-consuming process, but also fallible when considering overmuch specialist subjective judgments. Furthermore, emergency decision-makers may usually confront a dilemma of "the existing expertise cannot meet the requirements of response knowledge" in a natural disaster situation. Learning from historical cases is a basic way to quickly use successful experience and avoid past mistakes (Goh and Chua, 2009). More recently, case-based reasoning (CBR) has become an important way to support emergency decision-making in emergency response phase (Amailef and Lu, 2013). Accordingly, CBR can be highly helpful to improve the existing CI risk response.

The origins of CBR were held by Schank and Abelson (1977). They proposed that case-based reasoning can provide a method simulating the human way of cognition and learning which generates the proper solution for the target problem by adapting previously successful similar cases. Afterwards, the 4R model including case retrieval, reuse, revision and retention was presented by Aamodt and Plaza (1994), also case representation (Amailef and Lu, 2013; Lu et al., 2013) and case repartition (Finnie and Sun, 2003) have been considered. Based on this, CBR has increasingly attracted more and more attention in emergency response management. For case representation, an original and simple way of case representation is to use problem-solution pairs with the related features (Vong et al., 2011). Then, for better illustration, knowledge representation methods such as frame model (Liao et al., 2012, Liao et al. (2011)) and ontology model (Amailef and Lu, 2013; Delir Haghighi et al., 2013; Malizia et al., 2010) have been employed to express emergency case, which can lay the foundation to support CBR in building case structure and implementing query operation. With respect to case retrieval, the objective is to determine and find the similar cases (Aamodt and Plaza, 1994). Liu et al. (2012a) used the nearest neighbor method based on close degree to calculate disaster scenario similarity. In view of complex data situation, Fan et al. (2014) developed a new hybrid similarity measure method by comparing feature values with five datatypes including crisp number, crisp symbol, interval number, fuzzy linguistic variable and random variable. These approaches are basically used to match the disaster scenario to find out the similar cases. Furthermore, Lu et al. (2013) introduced structural similarity based on semantic network to compare two different case structures. In view of case reuse, it is to copy and adapt the solutions of the selected similar cases, and the transformational adaptation and derivational adaptation are the two main basic methods for adapting the similar cases (Aamodt and Plaza, 1994; Carbonell, 1986). Fan et al. (2015) illustrated a case adaptation method by deleting, adding and modifying unsuitable response strategies to generate practical response strategy plan. What is more, Liao et al. (2012) proposed an improved genetic algorithm to achieve case adaptation for environmental emergency preparedness considering quantitative calculation. In addition, Zhang et al. (2015b) introduced an improved case adaptation method that integrates the multi-objective genetic algorithm with grey correlation analysis for power grid under wind disasters. It is noted that case revision and retention are the tasks after applying the reused solutions in the target case (Aamodt and Plaza, 1994), thus the two steps will not be discussed in this paper related to CI risk response in a natural disaster situation.

It can be observed that CBR can provide a more efficient way to respond to the target CI risks in natural disaster situation. According to the literature review of emergency CBR, case representation model in previous studies is actually a type of retrieval-oriented model, which is not a systematic expression to support CBR. Besides that, although most of studies put emphasis on how to retrieve the similar cases, the existing approaches are too coarse to get the most feasible and effective solutions from limited source cases. On the other hand, CBR is useful to generate solutions in more realistic way, but seldom used for CI protection.

In light of the related studies (Amailef and Lu, 2013; Fan et al., 2015; Lu et al., 2013), the aim of this paper is to extend the application of CBR on UWSN risk response. We will also propose a new way to make full use of historical cases. In general, there are three aspects of this problem that need to be addressed. The first aspect involves case representation. In accordance with the opinions of Amailef and Lu (2013) and Lu et al. (2013), the ontology model is selected to represent UWSN risk case, which is easy to be shared and integrated for automated identification, knowledge acquisition and reuse. By contrast, we not only use ontology model to express disaster scenario features and UWSN risks, but also the response strategies. The second aspect relates to case retrieval. Unlike the research of Fan et al. (2015), the selection priority of response strategies is determined by the local risk criticality similarity after obtaining the similar case set based on a two-step case retrieval method. The third aspect refers to case copy and adaptation. A scenario-based case reuse method is presented to generate practical response strategy plan. Furthermore, a case study is carried out to test the feasibility and effectiveness of the proposed method.

The rest of the paper is organized as follows. In Section 2, the UWSN protection and research framework will be explained. Section 3 illustrates the use of ontology model to express UWSN risk case. Section 4 presents a two-step case retrieval method, and a scenario-based case reuse method will be given in Section 5. For better illustration, Section 6 shows a case study in Z City, China. This paper ends with conclusions that summarize the main contributions and suggestions on future works.

2. UWSN protection and research framework

2.1. UWSN protection

UWSN is a system to supply water for city, which contains engineered hydrologic and hydraulic components (Waikhom and Mehta, 2015). According to the related studies (Pietrucha-Urbanik, 2015; Waikhom and Mehta, 2015), we consider that UWSN mainly consists of three main sub-systems (see Fig. 1): water purification system, water pressurizing system and water distribution system. The functions of water purification system are to collect raw water from the raw water sources such as seas, lakes, rivers, underground aquifers, etc., produce pure water in the water plants and store the product water in the water storages like tanks. Water pressurizing system such as pumping stations can provide the pressure for water distribution. Water distribution system namely water supply pipe network can allocate and send the product water to factories, companies, residential areas, schools, etc.

Nowadays the robustness and resilience of UWSN can remain at a high level in normal situation, and most of risks can be mitigated with effective emergency preparedness. However, in case of natural disaster such as typhoon, rainstorm, flood, and landslide, it may lead to unimagined consequences. As highly critical disturbance, natural disaster can directly influence the nodes and edges of UWSN with high