Post-disaster Recovery Planning of Interdependent Infrastructure Systems: A Game Theory-Based Approach

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ABSTRACT: Optimizing the post-disaster recovery of damaged infrastructure systems is essential to alleviate the adverse impacts of natural disasters to community and enhance their disaster resilience. Post-disaster infrastructure recovery planning aims at achieving efficient and effective recovery of the already damaged infrastructure systems. As a result of infrastructure interdependencies, the complete functional restoration of a facility in one infrastructure system relies on not only the physical recovery of itself, but also the recovery of the facilities in other systems that it depends on. This study introduces the Interdependent Infrastructure Recovery Planning (IIRP) problem, which aims at optimizing the assignment and scheduling of the repair teams for an infrastructure system with considering the repair plan of the other infrastructure systems during the post-disaster recovery phase. Key characteristics of the IIRP problem are identified and a game theory-based IIRP decision framework is presented. Two recovery time-based performance metrics, the *total facility recovery waiting time* and *total service restoration waiting time* are introduced and applied to evaluate the efficiency and effectiveness of the post-disaster recovery plan. The IIRP decision framework is illustrated using the interdependent power and water systems of the Centerville virtual community subjected to seismic hazard.

KEYWORDS: decision-making; Dynamic Integrated Network model; game theory; infrastructure recovery optimization; interdependency.

1. INTRODUCTION

Proper functioning of the infrastructure systems in a community is essential for the social stability and economic prosperity. Natural and manmade disasters in recent decade witnessed severe damages of the civil infrastructure systems, which led to widespread service disruptions to the communities during the recovery phase. Due to the interdependencies among infrastructure systems, the complete recovery of a facility in one system depends not only on the physical recovery of itself, but also on the recovery of the facilities in other systems that it depends on. Therefore, considering infrastructure interdependencies in post-disaster recovery planning is important to achieve a more efficient and effective recovery.

Numerous studies and projects have been performed on developing methodologies to model the performance of interdependent infrastructure systems after disruptive events. The methodologies are generally grouped into five types: agent-based method, system dynamics-based method, network-based method, economic theory-based and others (Pederson et al., 2006; Ouyang, 2014). Most of the existing methodologies are capable of considering the physical, and sometimes, cyber interdependencies between different infrastructure systems (Rinaldi et al., 2001; He & Cha, 2019a). These methods have been widely applied to simulate the post-disaster recovery of various interdependent infrastructure systems, including power, water, transportation, telecommunication systems, etc.

However, unlike these extensive literatures on modeling the infrastructure performance after disruptive events, only limited studies exist on post-disaster recovery optimization decision making. Miller-Hooks et al. (2012) developed a stochastic model to maximize the transportation system resilience by optimizing the post-disaster recovery scheduling. Zhang et al. (2017) proposed a resilience-based framework to solve the post-disaster recovery scheduling problem for road-bridge transportation network. These few existing decision frameworks on infrastructure recovery schedule optimization tend to only focus on the transportation system, while neglecting the interdependencies among different infrastructure systems during the post-disaster recovery phase.

Furthermore, performance metric of the whole interdependent infrastructure systems that can be utilized for supporting the infrastructure recovery planning decision making has not been established well yet. The existing post-disaster infrastructure performance metrics can be classified into three categories. Metrics in the first category focus on assessing the performance of infrastructure systems only at the time when hazard occurs, such as reliability, vulnerability, robustness, flexibility, survivability, etc. (Grubesic & Murray, 2006; Chen et al., 2013; Faturechi & Miller-Hooks, 2014). The second type measures the infrastructure performance over time following a disruptive event and example metrics include connectivity, accessibility, flow capacity, travel time/distance, water pressure, etc. (Guidotti et al., 2016; Zhang et al., 2017; He & Cha, 2018a). The third type of the metrics focuses on the entire recovery curve and evaluates the efficiency (e.g.: recovery time, rapidity) or effectiveness (e.g.: resilience, skewness) of the overall recovery process (Sharma et al., 2018). Even though these existing infrastructure performance metrics all have their own merits in evaluating the infrastructure system performance under disruptive events, most of them emphasize on the functionality of the infrastructure systems, but fail to consider the service disruptions to the community. Besides, some metrics are designed to evaluate the functionality of one specific type of infrastructure system, which makes them hard to be extended to measure the performance of the integrated infrastructure network where several interdependent infrastructure systems are modeled together.

This paper first introduces the Interdependent Infrastructure Recovery Planning (IIRP) problem and a game theory-based decision support framework which could support strategic post-disaster recovery planning with considering infrastructure interdependencies. Then, two recovery time-based performance metrics are introduced to evaluate the efficiency and effectiveness of the post-disaster recovery plan. Finally, the presented IIRP decision framework and the performance metrics are illustrated using a case study on Centerville virtual community.

2. INTERDEPENDENT INFRASTRUCTURE RECOVERY PLANNING

2.1. Introduction of the IIRP Problem

In the post-disaster recovery phase, the main objective of the infrastructure owners is to repair the damaged infrastructure facilities and restore the service to the customers in a timely manner. The decisions of the infrastructure owners oftentimes can be summarized as determining *how many* repair teams need to be sent to the affected region, and *which team* should repair *which facility* at *what time*. The IIRP problem is introduced to guide infrastructure owners determining the optimal assignment and scheduling of their repair teams during the post-disaster recovery phase with considering the recovery of its interdependent infrastructure systems. Some key characteristics of the IIRP problem are defined and summarized in Table 1.

The proposed IIRP problem is comparable to game theory. Game theory deals with the problem where multiple decision makers decide independently, but contingent upon the actions taken by the other decision makers (Myerson, 2013; Herrmann, 2015). The IIRP problem also focuses on multiple decision makers from several interdependent infrastructure systems, one infrastructure owner's decision about the recovery strategy would be influenced by the strategies implemented on the other systems that his/her system depends on. The IIRP decision-making process using a game theory-based approach is discussed next.

Table 1: Key characteristics of the IIRP problem.

Decision objective	Repair the damaged infrastructure network and restore the service to the end-users as efficiently and effectively as possible.
Decision makers	Infrastructure owners, such as utility companies, railroad companies, local Department of Transportation, etc.
Decision phase	Post-disaster recovery phase
Decision constrains	Limited number of repair crews, available resources, policy requirements for system performance, etc.
Decision criteria	Recovery time, service restoration time, resilience, skewness, cost, total facility recover waiting time, total service restoration waiting time, etc.

2.2. Decision Framework for the IIRP Problem

A game theory-based decision framework to solve the IIRP problem with two decision makers from two interdependent infrastructure systems is shown in Figure 1. The framework could be easily expanded if more infrastructure systems are taken into consideration. The decision process for each infrastructure system begins by estimating an initial number of repair teams assigned. The optimal repair sequence to repair all damaged facilities in this system given the initial number of repair teams (step (1) in Figure 1) is obtained by using some optimization techniques, such as enumeration, genetic algorithms, linear programming and so on. Then, this optimal repair sequence is examined with the recovery of its interdependent infrastructure systems to determine whether its recovery could be further improved. If the recovery of this system can be further improved, and its current recovery performance does not meet the acceptable performance level, and there are more repair teams available, then another team is added. This recovery optimization process for each infrastructure system terminates when its recovery could not be further improved, or when the recovery performance has met the acceptable level, or when no more repair teams are available. The resulted number of repair teams and the corresponding optimal repair sequence form the optimal post-disaster recovery strategy for this system. This decision framework is especially useful for the decision makers from one infrastructure system when the recovery plans of its interdependent systems are available.

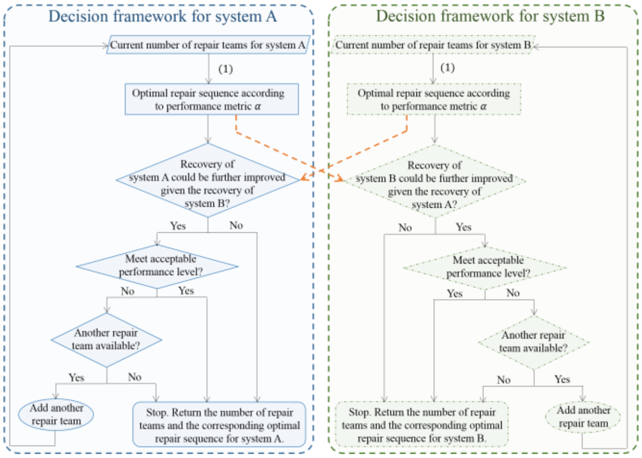

Figure 1: A game theory-based decision framework for IIRP problem with two decision-makers.

3. RECOVERY TIME-BASED PERFORMANCE METRICS

Two recovery time-based performance metrics are introduced in this study to evaluate the efficiency and effectiveness of the post-disaster recovery plans. The *total facility recovery waiting time* (TFRWT) is defined as the total recovery time of all the damaged infrastructure facilities in a network, which represents the efficiency of the recovery work. The *total service restoration waiting time* (TSRWT) is defined as the total waiting time for all the end-users getting the infrastructure service back, and represents the effectiveness of the recovery plan. These two metrics deviate from the existing infrastructure performance metrics in the following aspects: (1) they measure the overall performance of the entire infrastructure network over the whole post-disaster recovery phase, which makes them suitable for comparing different recovery plans. (2) They are not specific to one infrastructure system and are applicable to measure the performance of any infrastructures, either separately or as an integrated network. (3) TFRWT still focuses on the infrastructure systems while TSRWT takes the service disruptions to the end-users into consideration. (4) They are straightforward and easy to be computed. (5) They can be converted into other existing infrastructure performance metrics, such as resilience (He & Cha, 2019b).

4. CASE STUDY: CENTERVILLE INFRASTRUCTURE RECOVERY PLANNING

The IIRP problem is illustrated with a case study on post-disaster recovery planning of the interdependent power and water systems in Centerville subjected to seismic hazard. The proposed decision framework in Figure 1 and performance metric TSRWT are used to solve this example IIRP problem.

4.1. Centerville IIRP Problem Definition

Centerville is a virtual community developed by the NIST-Funded Center for Risk-based Community Resilience Planning as a testbed (Ellingwood et al., 2016). Centerville is located in a Midwestern State in the US with size of approximately 8 km by 13 km and population of about 50,000. A schematic of Centerville's building zones, electric power and potable water systems is shown in Figure 2. The 17 end-user facilities serve as the demand nodes of power and water systems. Some critical facilities in the water system also depend on the functioning of power system for proper operation.

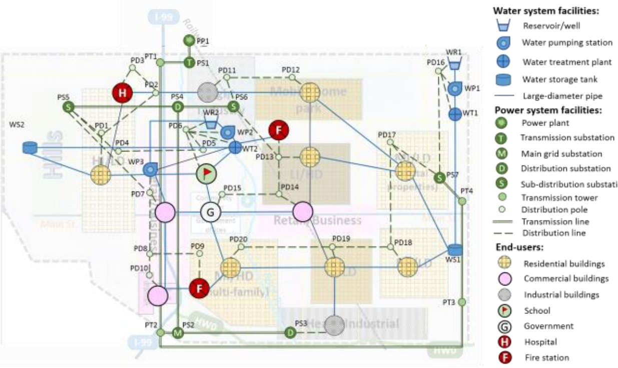

Figure 2: Critical infrastructure and end-user facilities in Centerville.

Centerville suffers from an earthquake with magnitude of 6.5 and epicenter at about 25 km southwest of the city. The PGA, PGV and PGD at different locations in Centerville were obtained from the ground motion prediction equations by Fernandez and Rix (2006). The mean PGA, PGV and PGD at different locations in Centerville are 0.2742g, 17.0057 cm/s and 4.3116 cm, respectively, with standard deviation of 0.0149g, 1.5033 cm/s and 0.4261, respectively.

The expected damage level of the infrastructure facilities under scenario seismic hazard was calculated from the probability of damage state curves in HAZUS-MH and the damage level definitions for different damage states in ATC-13 (Applied Technology Council, 1985; FEMA, 2003). According to ATC-13, a damage level greater than 0.1 indicates that the corresponding facility suffers from significant damage that warranting repair. As a result, 8 out of 32 power facilities and 5 out of 9 water facilities in Centerville suffer different levels of damage and require repair after the disaster.

The Centerville Department of Public Works (CDPW) is in charge of the post-disaster recovery works of the damaged power and water systems in Centerville (Ellingwood et al., 2016). CDPW's overall objective is to repair the damaged facilities and restore the utility service to all the end-users as fast as possible. It is assumed that 2 power repair teams and 1 water repair team in Centerville are readily available. Besides, 2 more repair teams for each system are located in a city adjacent to Centerville and could reach the damaged facility sites in Centerville to support the repair work a day after, if needed. Asking the outside repair teams to aid the recovery for Centerville infrastructure systems requires extra cost and coordination of CDPW. However, CDPW has the policy of restoring the utility service within 2 weeks (14 days) after a disruption event. Thus, the head of the power or water sector in CDPW each decides a recovery plan, which could minimize the service disruption time while using as less outside repair teams as possible but meet the policy requirement. As both power and water sectors are within the CDPW, the repair plan of one system could be shared with the other sector. A summary of this example IIRP problem for Centerville is shown in Table 2.

Table 2: Summary of the IIRP problem for Centerville case study.

Decision makers	(i) Power sector head for the power system and (ii) water sector head for the water system, both within the CDPW.
Objective for each decision maker	Repair the damaged infrastructure facilities and restore the utility service to all the end-users as fast as possible.
Tasks for each decision maker	(i) Determine the number of repair teams used; (ii) Determine the assignment and scheduling of the repair teams to repair all the damaged infrastructure facilities.
Constraints for each decision maker	(i) Limited number of repair teams: 2 local + 2 outside power repair teams, and 1 local + 2 outside water repair teams. (ii) Service restoration time for all the end-users should be within 14 days.
Decision criterion	TSRWT

The case study IIRP problem defined in Table 2 is solved using the proposed game theoretic approach shown in Figure 1. The optimal repair sequence under a certain number of repair teams (step (1) in Figure 1) is determined by first enumerating all possible repair sequences, then evaluating the recovery performance under each repair sequence using the Dynamic Integrated Network (DIN) model (He & Cha, 2018a, b & 2019a). The DIN model is briefly introduced in the next section before presenting the post-disaster recovery planning results.

4.2. Centerville Infrastructure Recovery Modeling Using Dynamic Integrated Network Model

A desired model to accomplish the recovery modeling task to solve the IIRP problem is one that could simulate the recovery of the infrastructure network at both the facility and system levels, and considers the dependency relationships between the facilities within and across infrastructure systems. The DIN model proposed by He and Cha (2018a, b & 2019a) has the above mentioned properties and is adopted to model the post-disaster recovery of the damaged Centerville facilities in this study. The general framework of the DIN model with input and example output information are shown in Figure 3. The DIN models the recovery of different power, water and end-user facilities in Centerville using a mathematical formula that considers different recovery rates of different facilities and the dependency relationships between them. In this study, it is assumed that the recovery of a damaged facility would not start until a repair team is available at that site, and the repair team cannot move to another damaged facility site until the current work is completed. One example output of DIN is the recovery schedule of damaged facilities over time (output ② in Figure 3). It shows which facilities are in repair at each time step. This output recovery schedule is useful to measure the efficiency and effectiveness of the post-disaster recovery work.

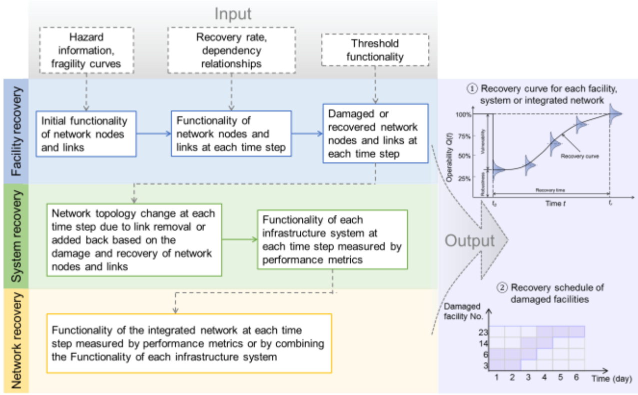

Figure 3: General framework of the DIN model.

4.3. Centerville Infrastructure Recovery Planning Results

In the initial step, 2 local power system repair teams and 1 local water system repair team are considered to repair 8 damaged power facilities and 5 damaged water facilities in Centerville. All possible repair sequences to repair the damaged facilities in each system are enumerated using permutation, then the optimal repair sequence for each system is determined based on TSRWT. If the recovery of an infrastructure system does not meet the acceptable performance level (<14 days), one more outside repair team would be assigned to assist the recovery. The process would end if the acceptable performance level is met, or no more repair teams are available. The intermediate optimal repair sequences obtained with varying number of repair teams used through the optimization process are shown in Figure 4.

It can be learned from Figure 4 that when only the local repair teams are used (iteration 1), the service restoration time of all end-users is 25 days, with TSRWT of 395 days for all 17 end-users under the optimal repair sequence. Since the service restoration time of 25 days exceeds the acceptable performance level (<14 days), and it is the recovery of damaged power facilities that drags the recovery process down, one more power repair team is added to accelerate the post-disaster recovery. In this scenario (iteration 2), the service restoration time reduced to 22 days, with TSRWT of 365 days under the optimal repair sequence. This time, the water system recovery drags the utility service restoration time down, so one more water repair team is added (iteration 3). It reduces the utility service restoration time for all end-users to 17 days with 96 days of decrease in TSRWT, which is a significant improvement. However, the utility service restoration time still have not met the policy requirement of less than 14 days, and it's attributed to the slow recovery of the power system, thus one more outside power repair team is assigned (iteration 4). In this case, the service restoration time finally drops to 13 days with TSRWT reduced to 205 days, which meet the policy requirement.

It's noted here that the optimal water system repair sequence using 2 repair teams (iteration 3 and 4) is indeed the "global optimal" solution for the water system in this case study IIRP problem, since the water service restoration time could not be further reduced. The only power transmission substation (PS1) directly connected to the only power plant (PP1) in Centerville suffers most severe damage and takes the longest time to recover (12 days). Although the other damaged power or water facilities could be physically repaired within the 12th day, they have to wait until the recovery of PS1 to restore their services. This unique situation highlights the importance of considering interdependencies between different infrastructure systems when planning the post-disaster recovery for individual systems. If the decision maker from the water system is not

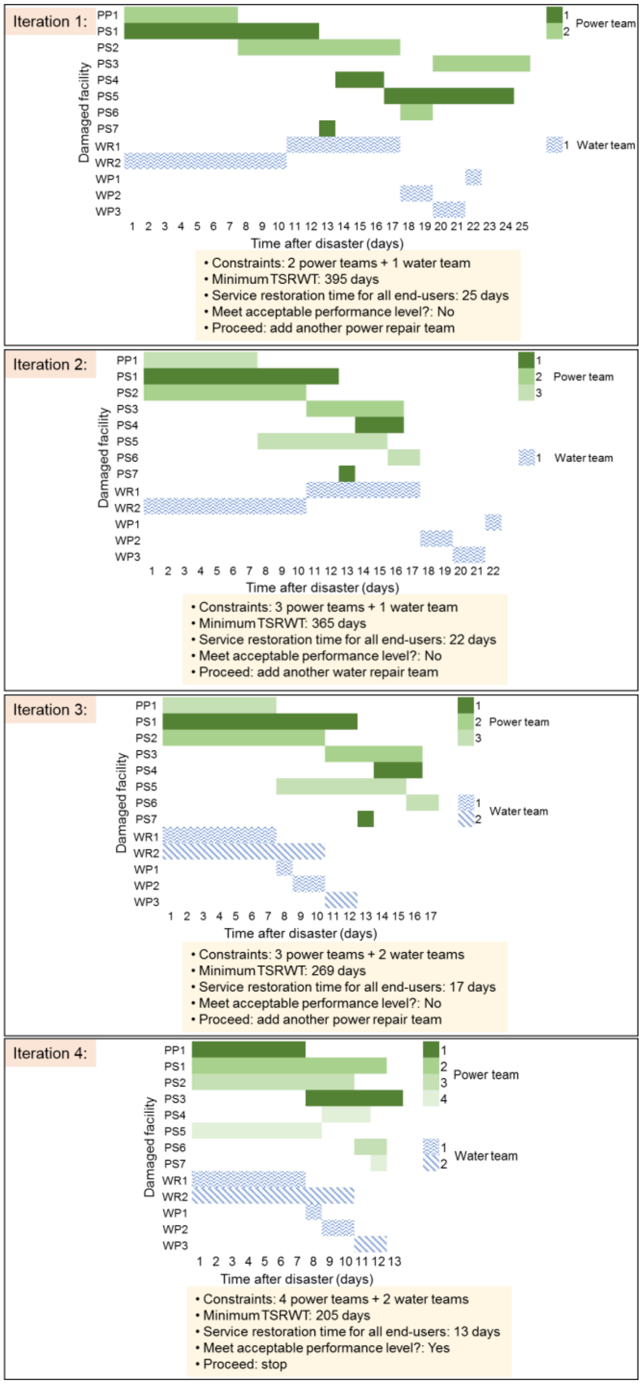

Figure 4: The intermediate optimal repair sequences obtained through the optimization process.

informed of the recovery plan of the power system on which it depends, he/she would likely add another water repair team available to further reduce the water system recovery time from 12 days to 10 days. However, if the decision maker from the water system is aware of the fact that the power service could not be restored until the 12th day, this extra water repair team would not be needed since no improvement of the water service restoration time (i.e. benefits) could be achieved by hiring another repair team (i.e. costs).

Another insight reveals from this case study is that different optimal repair sequences would be obtained if different decision criteria are used. Figure 5 shows two global optimal repair sequences for Centerville power and water systems under the repair team constraints in Table 2 determined by two different decision criteria: TSRWT or TFRWT. If the service restoration time for the end-users is the primary concern of the decision makers, the TSRWT or service restoration time for all end-users would be used as the decision criterion. The optimal repair sequence determined based on lowest TSRWT or minimum service restoration time for all end-users is shown on the left side of Figure 5. Using this criterion, the facilities that serve larger percentage of the end-users would be repaired first, such as PP1, PS1, PS2, WR1 and WR2 in this study, even though some of these facilities take a much longer time to be repaired (i.e. PS1, PS2). On the other hand, if the number of damaged facilities been repaired within a certain time period is in primary consideration, then TFRWT becomes a more suitable decision criterion to evaluate the efficiency of the repair work. The optimal repair sequence which yields the minimum TFRWT under the same constraints is shown on the right hand side of Figure 6. In this scenario, the facilities that take the shortest time to recover would be repaired first, such as PS4, PS6, PS7, WP1, WP2 and WP3 in this study. Under this scenario, the TFRWT could be reduced from 132 days to 91 days, but the TSRWT and service restoration time for all end-users both increases significantly (i.e. 101 days longer for TSRWT and 5 days longer for service restoration time of all end-users). This comparison shows that different decision criteria would yield different optimal post-disaster recovery plans, thus highlights the importance of using proper decision criterion before planning the post-disaster recovery of damaged infrastructure systems.

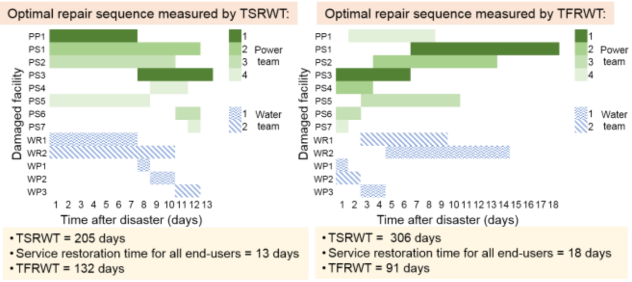

Figure 5: Optimal repair sequences of Centerville utility systems determined by TSRWT or TFRWT.

5. CONCLUSIONS

A game theory-based IIRP decision framework is introduced in this paper, which can support the risk-informed decision-making for post-disaster recovery planning of interdependent infrastructure systems. Solving the IIRP problem can assist the decision makers from infrastructure systems determining the optimal assignment and scheduling of their repair teams during the post-disaster recovery phase with considering the recovery plan of its interdependent infrastructure systems. The decision framework is applicable to any infrastructure systems under any disruptive events. Two recovery time-based infrastructure performance metrics are introduced to facilitate the comparison of the efficiency and effectiveness of different post-disaster recovery plans. The proposed decision framework and the recovery time-based performance metrics are illustrated by optimizing the post-earthquake recovery of power and water systems in Centerville. The analysis results highlight the importance of considering interdependencies between infrastructure systems, and using proper decision criteria when planning the recovery of individual systems.

One limitation of the IIRP problem is that the size of the problem could become extremely huge when many damaged facilities and/or repair teams are considered. Hence, it's necessary to develop more efficient algorithms or use heuristic approaches to solve the IIRP problem with good enough (approximate) solutions under reasonable amount of time.

6. ACKNOWLEDGEMENT

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