The International Emergency Management Society
2015 Annual Conference, 30th September - 2nd October 2015, Rome, Italy

Improving Critical Infrastructure Resilience through Scheduling of Firefighting Resources

Khaled Alutaibi [1,2]**, Abdullah Alsubaie** [1]**, and José Martí** [1]

[1] *Dept. of Elec. Comp. Engineering, UBC, Vancouver, Canada*
[2] *Civil Defence, Ministry of Interior, Riyadh, Saudi Arabia*
Email: {alkhaled, alsubaie, jrms }@ece.ubc.ca

ABSTRACT :
Despite the fact that a lot of efforts and resources have been invested in fire prevention, not all fire incidents can be averted. Recently, there has been more emphasis in emergency management on preparedness and response than protection and prevention. The concept of resilience including disaster preparedness, response, recovery, mitigation, and adaptation, can be employed to reduce the resulting direct and indirect impacts of a disaster. The objective of this paper is to evaluate the impact of allocating firefighting units during multiple fire incidents on the resilience of infrastructure systems. This paper proposes a methodology composed of three parts: 1) The Infrastructure Interdependencies Simulator (i2sim), 2) A loss function, and 3) A resilience measure. This methodology can be applied to any type of natural or man-made hazards, which might lead to the disruption of infrastructure systems. The proposed methodology is illustrated using a case study representing a petrochemical complex. The numerical results show that the best retrofit method to improve the resilience measure of the entire complex should consider optimization techniques for such decisions.

KEYWORDS:
resilience, disaster response, critical infrastructures, interdependencies, firefighting, industrial fires

1. INTRODUCTION

During the past several years, fire incidents have been one of the most common and costly disasters. These incidents can cause a large number of deaths and injuries, economic losses, and interruption of basic services. Increasing and complex interdependence of existing infrastructure systems are not only vulnerable to fires that they are directly exposed to, but also to indirect consequences to other systems. The US National Fire Protection Association (NFPA) reported that in 2011 the estimated economic losses, due to fires, was $14.9 billion. These losses include both property damage (direct losses) and business interruption (indirect losses) (National Fire Protection Association (NFPA) 2010) (National Fire Protection Association (NFPA) 2010). Despite the fact that a lot of resources have been invested in fire prevention, not all fire incidents can be averted. Also, recent incidents have highlighted the limitations of the existing response systems such as situational awareness, and rapid coordination of activities between emergency response departments (e.g. fire, police) (Collins et al. 2003). Increasingly the emphasis in emergency response has shifted from protection and prevention towards preparedness and response (Pant et al. 2014). The concept of resilience including disaster preparedness, response, recovery, mitigation, and adaptation, can be employed to reduce the resulting direct and indirect impacts of a disaster and recover in a timely manner.

In this work, we study the resilience of infrastructure systems under fire incidents. We assume that resilience depends on the effectiveness of the emergency preparedness and response plan. The effectiveness of emergency response plan includes prioritization of responses and optimal allocation of available limited resources. According to Bruneau, et al. (Bruneau et al. 2003), there are four dimensions that can improve resilience. These features are as the follows:

- Robustness: The inherent strength or resistance in any system to withstand a given level of stress or demand without degradation or loss of functionality.

- Redundancy: Ability of a system to satisfy the functional requirements using alternate options, choices, and substitutions in event of disruption, degradation, or loss of functionality.
- Rapidity: The speed with which losses are overcome and safety, serviceability, and stability are re-achieved.
- Resourcefulness: The ability to identify problems, establish priorities, and mobilize resources and services in emergencies to restore the system performance.

Although many of these dimensions have been evaluated as technically-based functions of the physical systems, quantifying resourcefulness, as a property, remains challenging because it relies on human skills and their abilities to respond and recover from disaster events (Cimellaro et al. 2010). In this work, the focus is on two of these dimensions (resourcefulness and rapidity) that track the reaction during extreme events. The system resourcefulness is evaluated by the ability to prioritize fire incidents and the optimality in mobilizing firefighting units. The system rapidity is evaluated by containing economic losses in production and by minimizing the recovery time.

In this paper, we propose a methodology to evaluate the impact of resource allocation decisions during fire incidents in improving infrastructure resilience. This methodology can be used for any type of natural or man-made hazards. It can also be used for other resource allocation problems in any interdependent environment such as telecommunications, transportation, electric power grids, and water supply systems.

The rest of this paper is organized as follows. Section 2 presents a literature review on works related to resource allocation during disasters. Section 3 describes the formulation of the resource allocation problem. Section 4 introduces the proposed methodology. Section 5 uses a test model, based on real data, to validate the performance of the proposed methodology. Section 6 concludes the paper by a discussion of limitations and future research directions.

2. LITERATURE REVIEW

The concept of emergency management has received considerable attention in recent years. In the literature, it is common to define four phases of emergency management: mitigation, preparedness, response, and recovery (Ajami & Fattahi 2009; Altay & Green 2006; Waugh & Streib 2006). The hazard mitigation phase involves the actions that are taken to prevent or reduce the impact of a disaster. The preparedness phase includes all pre-disaster actions such as planning and training. The response phase includes all the actions that are taken immediately after a disaster strikes, such as saving lives and minimizing damage to properties. The recovery phase involves all the actions to return life to normal and restore basic services (Waugh & Streib 2006).

Even though all phases are overlapping, the focus of this work is on the response phase. Whenever a disaster strikes, effective and efficient emergency response can be deeply influenced by efficient allocation of the available resources. In this respect, many researchers have focused on developing approaches dealing with allocation and deployment of emergency resources (Fiedrich et al. 2000; Kondaveti & Ganz 2009). Fiedrich et al. (2000) proposed a dynamic optimization model for allocating emergency resources to operational areas after an earthquake. The objective of the model is to minimize the total number of fatalities during the Search-and-Rescue period. Similarly, mathematical programming models are proposed for allocating and scheduling rescue units by Wex et al. (2014) and Schryen et al. (2015). Barbarosoglu et al. (2002) developed a hierarchical multi-criteria methodology for assigning helicopters tasks during a disaster relief operation. The focus of this work was to minimize the operational cost. Emergency response during multiple hazard events have been also addressed in several recent publications Dillon et al. (2009), Li et al. (2009), and Abkowitz et al. (2012). Most of the decision making process in these studies is based on risk prioritization.

Furthermore, there is some research considering resource allocation firefighting operations. Integrated fire behavior simulation and optimization to allocate firefighting resources has also been addressed in (Hu et al. 2011; Figueras i Jove et al. 2013; Ntaimo et al. 2008; Petrovic et al. 2012). While these models provide considerable insight into the interaction between fire dynamics and resource allocation, they are limited to specific type of fire (wildfires) and cannot be extended to fires in interdependent infrastructure systems. Also, they do not capture the emergency responders decision on economic losses during the response efforts. In this work, the proposed model incorporates the concept of infrastructure systems resilience in firefighting operations. This concept can assist emergency responders in allocating the optimal number of firefighting units during single/multiple fire incidents in order to minimize both the overall losses (direct and indirect) and the time required to return to normal operation.

3. PROBLEM DEFINITION

This research is mainly concerned with developing a methodology to evaluate the impact of allocating firefighting units during fire incidents on infrastructure resilience. Once a fire alarm signal is received, the response mobilization is started by dispatching different firefighting units from fire stations. Emergency responders must determine the efficient number of firefighters that should be allocated to mitigate the potential disruptions. The existing strong interdependence between infrastructure systems remains a challenge in modeling the consequences of fire incidents. Because such incidents and their cascading effects are becoming stronger and have impact on the infrastructure resilience, there is a significant need to evaluate the impact of the resource allocation process on infrastructure resilience.

In the analysis of infrastructure systems and emergence response behaviors, two major problem areas exist, namely:

a) An infrastructure system, I, is a set of production units related to each other, $I = \{P_1, P_2, P_3, \ldots, P_n\}$, where P_n is the nth production unit, and n is the total number of production units. Given a set of fire incidents $\{f(P_1), f(P_2), \ldots, f(P_n)\}$ what is the impact on the infrastructure system I ?

b) Given a set of firefighting units, $\{u_1, u_2, u_3, \ldots, u_q\}$, where u_q is the qth firefighting unit, q is the total number of available firefighting units, and a desired level of resilience, $R(I)$. what is the best allocation scheme of the available firefighting units during suppression time, $[0, T_S]$, such that $Ts = \{(u_1, f(P_1)), (u_2, f(P_2)), (u_3, f(P_2)), \ldots\}$, $\forall\, T_S \in [0, T_S]$ to maintain a desired resilience level, $R(I)$?.

4. PROPOSED METHODOLOGY

The purpose of the proposed methodology is to study the impact of allocating firefighting units during multiple fire incidents on the resilience of infrastructure systems. The proposed methodology is composed of three parts: 1) The Infrastructure Interdependencies Simulator (i2sim), 2) A loss function, and 3) A resilience measure. The i2Sim provides a simulation environment to represent multiple interdependent infrastructure systems (or production units). The loss function is calculated using both direct and indirect interruptions in production process. The resilience measure is evaluated by the performance and functionality of the infrastructure under the considered scenario. The integration of these three parts makes it possible to quantify the impact caused by potential fire incidents. The overall structure of the proposed methodology is illustrated by the flowchart in Figure1.

4.1. Infrastructure Interdependencies Simulator (i2Sim)

In order to model multiple dissimilar systems, a common ontology is required to capture the emergent behavior arising between these systems. Also, an effective emergency response requires consideration of the interaction among multiple layers: decision layer, damage layer, finance layer, and production layer.

The infrastructure interdependencies simulator (i2Sim) framework proposed by Marti (2014) provides a structure to capture these interactions. This framework has been used in modeling infrastructure systems in different emergency response applications (Wang & Marti, 2012; Alsubaie et al., 2013; Khouj et al., 2014).

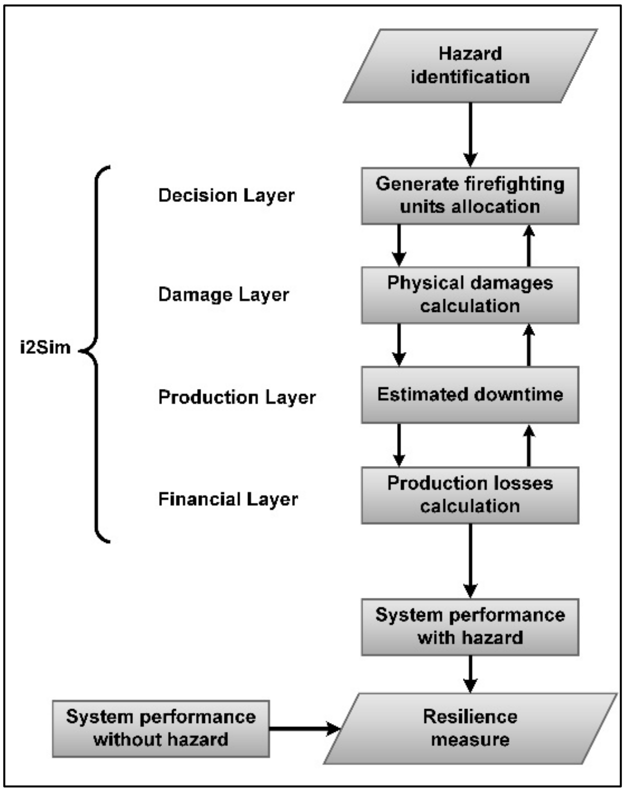

Figure 1 Flowchart describing the framework for system resilience measure.

The i2Sim ontology uses a cell-channel approach and represents cells functions using input-output relationships. i2Sim has three main components to model infrastructure systems: (1) Cells (production units) which are used to model the system components; (2) Channels (transportation units) which represent the relationships between the system components; and (3) Tokens (resources) which are the resources needed in the system. Figure 2 shows the conceptual model of an i2Sim cell and channel. For each cell, there is one output (product) and one or more inputs. The relationship between the inputs and the output is predefined in a lookup table, the "Human Readable Table (HRT)". The operating states of each cell is determined by three factors: (1) the availability of the input resources, (2) the level of physical damage of the cell, Physical Mode (PM), and (3) external information inputs (modifiers) that are received as input into the cells.

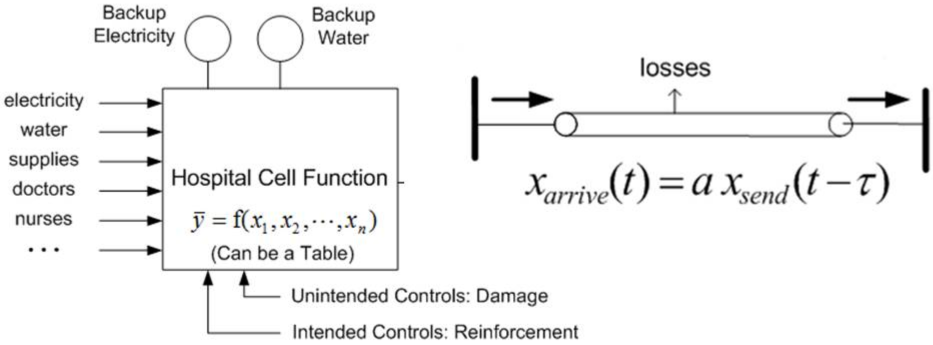

Figure 2 Conceptual cell and channel models (Martí 2014).

During extreme events such as earthquakes, fire, and floods, the modifiers play the main role in exchanging the available information between multiple layers: decision layer, damage layer, finance layer, and production layer. The i2Sim simulation layers are shown in Figure 3. The availability of these information assists emergence responders to maintain essential services to reduce the risk to life and properties in the event of an emergency.

The flowchart above illustrates the proposed methodology (Figure 1). This process begins by hazard identification and characterization. In this work, a multiple fire incidents scenario is presented. Each fire has a different level of severity. This level is mapped to a damage level and a required number of man-hour for the suppression process. Based on these information, emergency responders (decision layer) generate the allocation schedule of the available firefighting units. The decision layer includes all the decisions (actions) to be executed based on information supplied from the other layers. These decisions are evaluated in the damage layer. After each decision, the physical state of the system components is measured at the damage layer and represented as physical mode (PM). The impact of these damages is translated into downtime at the physical layer (production layer). During the downtime period, the degradation in production can be measured from the i2Sim cells' output.

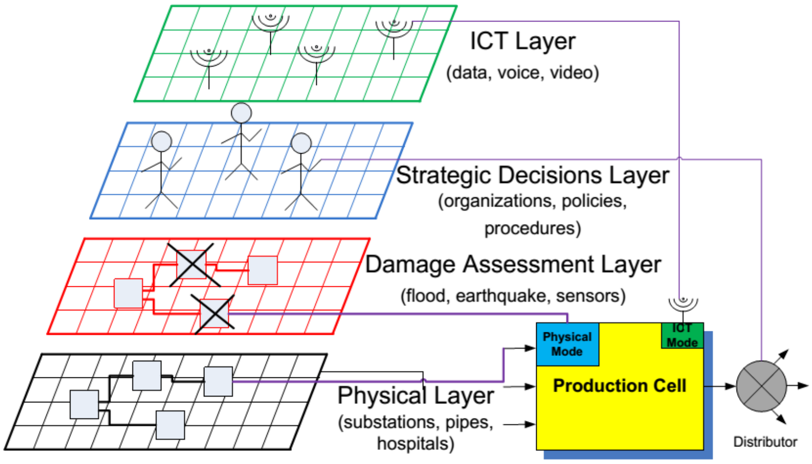

Figure 3 Simulation layers (Martí, 2014).

4.2. Loss Function

Economic losses (production losses) usually comprise direct losses and indirect losses. These losses are calculated from the direct and indirect interruptions in production process at the finance layer. The cost of the total losses in production can be expressed by the following equation:

$$losses = \sum_{t=1}^{T_{RE}} \sum_{i=1}^{n} \sum_{j=1}^{m} (PL_{ij}(t) \times V_j) \qquad (4.1)$$

where t is the time of interruption in recovery time T_{RE} time intervals; n is the number of affected facilities due to the fire incident; m is the number of interrupted products in each facility, PL_{ij} is the amount of lost production of product j from facility i, and V_j is the market value of material/service j.

At this point, the system performance under the identified hazard can be evaluated and compared with a desired level. In the following section, we describe the methodology of our approach in measuring infrastructure resilience.

4.3. Resilience Measure

Resilience was originally introduced as a property of systems by Holling in 1973 (Holling 1973). Since that time, the concept of resilience has been studied in a large number of disciplines such as ecology, psychology, sociology, economics, and engineering. Increasingly, resilience is recognized to be an important dimension of the sustainability of infrastructure systems. Bruneau et al. (2003) emphasize that resilient systems reduce the probability of failure; the consequences of failure such as economic losses; and the time for recovery.

Infrastructure resilience can be defined as the ability to reduce the magnitude and/or duration of disruptive events (National Infrastructure Advisory council (NIAC) 2009). Resilience, as a property of complex systems, can be measured in one of two ways: the amount of disturbance a system can withstand without changing its original state (Holling 1973), and by the time taken for a system to recover after a disturbance (Pimm 1984). In this sense and after analyzing the literature, the definition provided by Cimellaro et al. in (Cimellaro et al. 2010) has been adopted. Cimellaro et al. (2010) define resilience (R) as:

> *".. .a function indicating the capability to sustain a level of functionality or performance . .. over a period defined as the control time (T_{LC}) that is usually decided by owners, or society... "*

Figure 4 shows hypothetical system functionality curve with the effects of event, *E*. This figure provides a general overview of the time dependent system functionality and illustrates the important times during system response. As expected, system functionality under the effects of the event degrades from the normal operating level. This functionality with respect to the time of event occurrence can be divided into three stages: pre-event ($t < t_{E0}$), recovery time ($t_{E0} < t < t_{E0} + T_{RE}$), and post-event ($t > t_{E0} + T_{RE}$). In the pre-event stage, the system operates under normal conditions. During the recovery period, the system operates under the influence of the hazard. In the post-event stage, the system returns to normal operation.

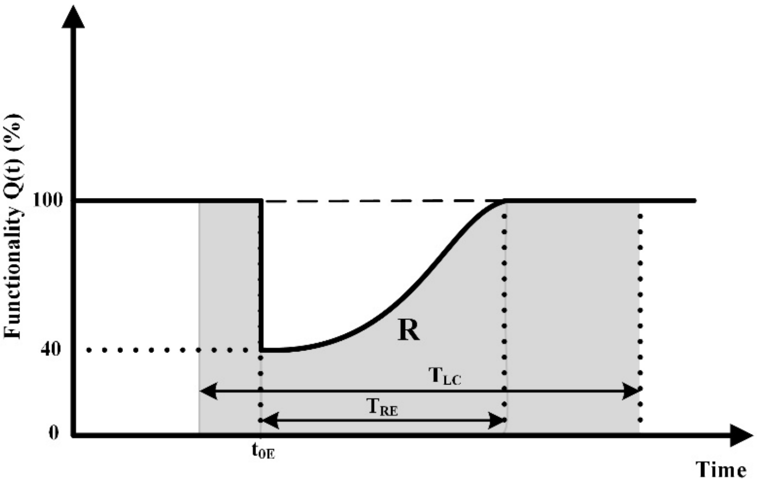

Figure 4 Graphical representation of resilience.

Analytically, the resilience measure can be expressed by the following equation (Cimellaro et al. 2010):

$$R = \int_{t_{0E}}^{t_{0E}+T_{LC}} Q(t)/T_{LC} dt \tag{4.2}$$

where *Q(t)* is the functionality of the system; T_{E0} is the time of occurrence of event *E*; T_{LC} is the control time of the system.

For the infrastructure systems, the functionality can be expressed as the economic losses in production. These losses include both losses in production due to a disturbance (direct losses) and business interruption due to degrading in production (indirect losses). Therefore, analytical functionality *Q(t)* of the infrastructure system is given by the following expression:

$$Q(t) = 100 - [(L_D(T_{RE}) + L_{ID}(T_{RE})] \tag{4.3}$$

where L_D is the direct losses; L_{ID} is the indirect losses; T_{RE} is the recovery time from event *E*. Both direct and indirect losses can be measured through the i2Sim cells' output.

5. CASE STUDY

The methodology described above has been applied to a petrochemical industry as an example of an interdependent system. The petrochemical industry uses oil and natural gas as major raw materials to produce plastics, rubber and fiber materials and other intermediates. These intermediates can be converted into thousands of industrial and consumer products having a huge impact on the economy of a nation, these products act as raw materials for other industries. Fires incidents could cause a mass of damages within the petrochemical complex and other industries. According to the Kuwait Finance House (KFH): the global petrochemicals market was valued at $472.06 billion in 2011 and is expected to reach $791.05 billion by 2018. In terms of volume, the global petrochemicals consumption is expected to reach $627.51 million tons by 2018 (The Kuwait Finance House (KFH) 2013).

In this study, we consider a petrochemical complex consisting of six chemical plants that produce different petrochemical materials. This complex is modeled based on a real data from previous work. The production process in the petrochemical plants is modeled using i2Sim to simulate multiple fire incidents. Interdependencies between petrochemical plants are incorporated in evaluating the consequences of these incidents. Figure 5 shows the structure of this complex, and the connections each plant has to one another.

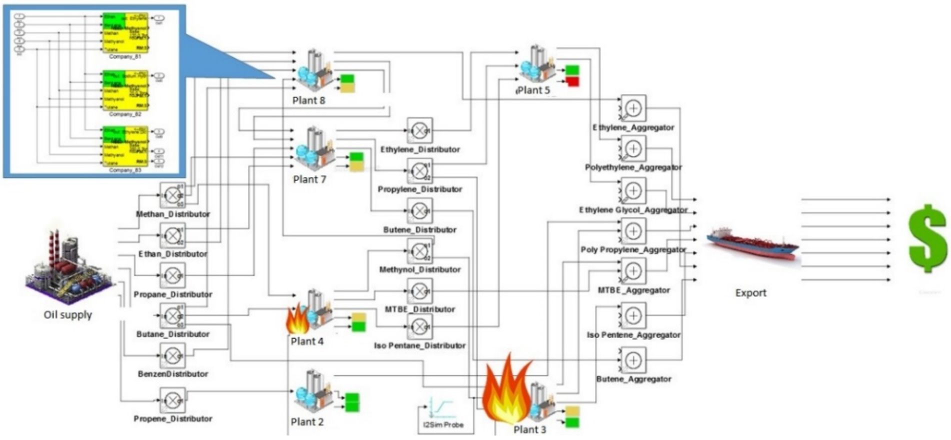

Figure 5 i2sim model.

There are 100 firefighters allocated in five different fire stations forming 20 firefighting units. For fire incidents, two fire incidents are considered: fire 1 in Plant 3 and fire 2 in Plant 4. We assume that the required man-hour for suppressing fire 1 and fire 2 are 600 and 300, respectively. Furthermore, four different allocation of firefighting units to improve the resilience of the petrochemical complex were considered for this case study (as shown Table 1). Method 1 and 2 represent common actions during multiple-fire incidents which are to allocate the firefighting units based on the fire size, giving more units to the larger fire. Method 3 shows the impact of treating both fire incidents equally. Method 4 represents the allocation decision based on an optimization technique such as dynamic programming, integer programming, and genetic algorithm. In our work, reinforcement learning (RL) technique is used to generate the scheduling decisions of the firefighting units.

Table 1 Allocation methods

Allocation Methods	Methodology	Description	Objective
Method 1	70%-30%	70% to the large fire, 30% to the other fire	Suppress large fire first
Method 2	60%-40%	60% to the large fire, 40% to the other fire	Suppress large fire first
Method 3	50%-50%	50% to each fire	Treat all fire incidents equally
Method 4	Optimization	Assign units based on optimization technique	Suppress fires to minimize losses

It is assumed that the operation of life saving is not included in this work. Also, recovery cost of the production process due to business interruption are not considered in this example. Figure 6 shows the performance (production level) for the petrochemical complex within one year period.

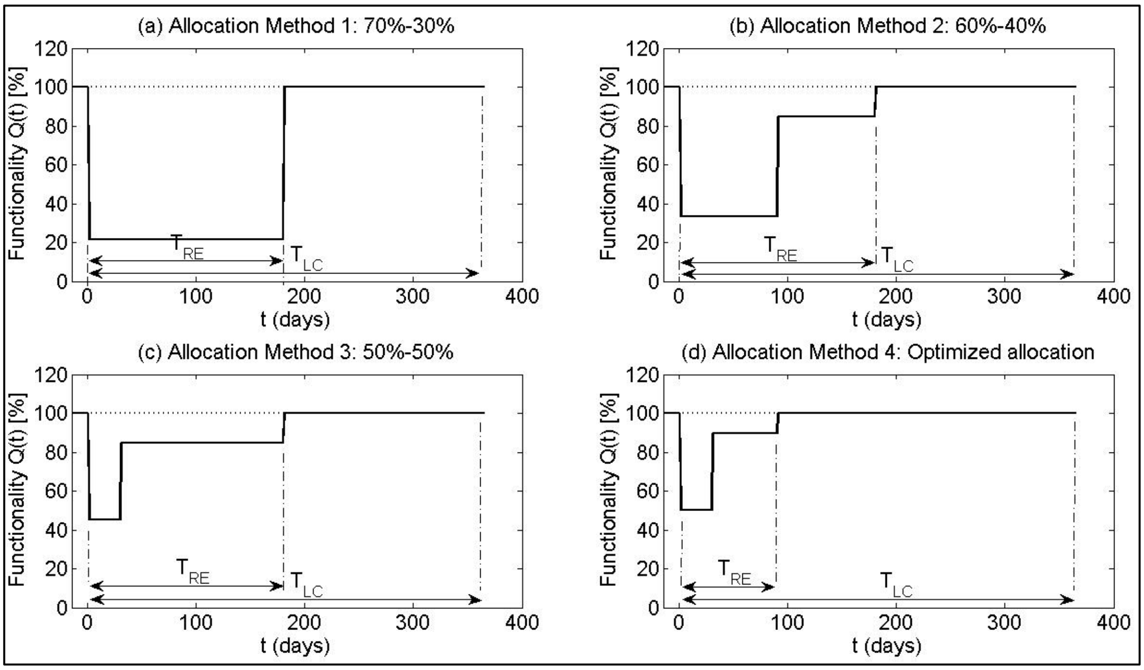

Figure 6 Functionality of petrochemical complex after different allocation methods during fire incidents.

The expected equivalent production losses for each allocation method are shown in the third column of Table 2, along with the recovery period considering an observation period TLC of 365 days.

Table 2 Costs, recovery time and resilience of petrochemical complex for different allocation strategies.

Allocation Methods	Recovery Time T_{RE} (days)	Production Losses ($ Millions)	Resilience R(%)
Method 1	180	$5,768	61.25%
Method 2	180	$3,008	79.78%
Method 3	180	$1,605	89.21%
Method 4	90	$858	94.23%

The complex resilience value is calculated according to Eqn. 2 from the control time TLC, 365 days in this example, as shown in Figure 7 .The resilience values are summarized in Table 2. For this case study, it is shown that the optimized allocation has the largest resilience value of 94.23%, when compared with the other three methods, and it is the least losses in production ($ 858 millions). However, if the common action (method 1) is taken, the complex resilience is reduced to 61.25%, and the production losses increased drastically to $5,768 millions. This means that the optimizing resource allocation process during fire incidents improves the infrastructure resilience.

We conclude that effectiveness of the emergency preparedness and response plan has a high impact on improving infrastructure resilience.

6. CONCLUSION

In this paper, we presented the concept of resource allocation process during fire incidents with respect to the infrastructure resilience. Resourcefulness and rapidity both revolves around the ability to maximize the utilization of available resources and to minimize the economic losses by minimizing the recovery time. We have introduced a methodology to evaluate the impact of allocating firefighting units during multiple fire incidents on the resilience of infrastructure systems. This methodology allows exploration of how different resource allocation techniques affect infrastructure resilience. It can be used for any type of natural or man-made hazards, which might lead to the disruption of the infrastructure systems. It can also be used for other resource allocation problems in any interdependent environment such as telecommunications, transportation, electric power grids, and water supply systems. This paper explores the impact of allocating limited number of firefighters during multiple fire incidents using a case study of a petrochemical complex. We conclude that the decisions of allocating firefighting units is crucial for ensuring an acceptable level of production after suppression. Further more, the best retrofit method to improve the resilience measure of any infrastructure system should consider optimization techniques for such decisions.

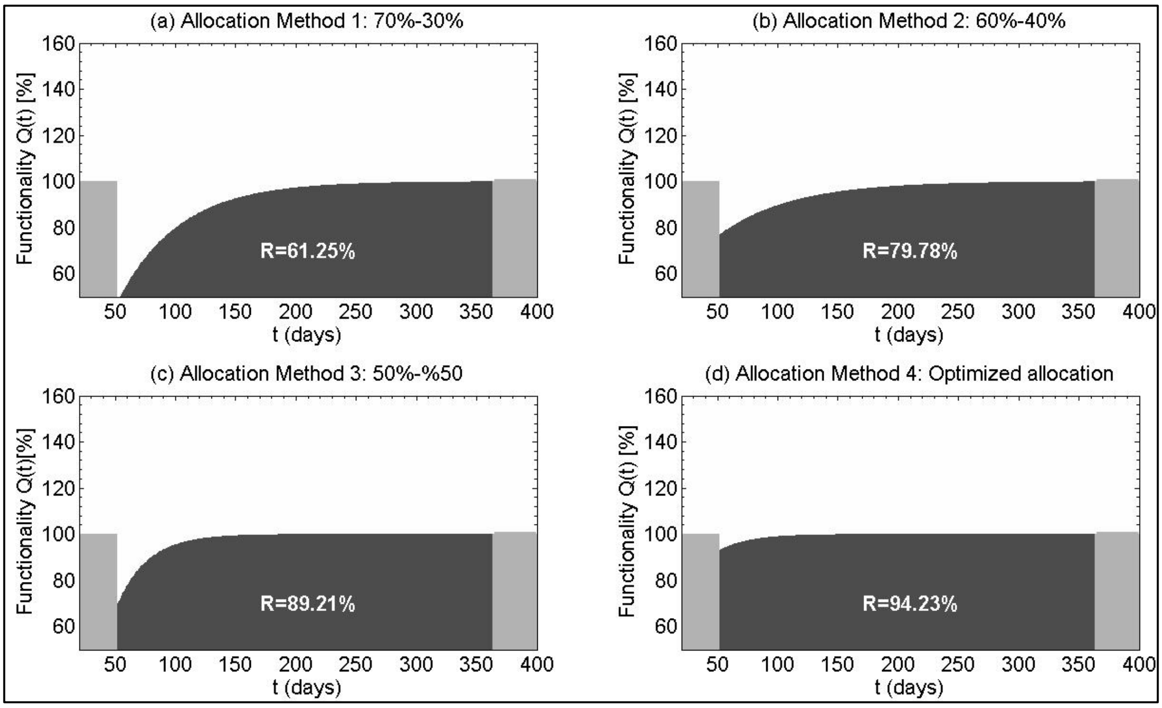

Figure 7 Functionality curves.

ACKNOWLEDGMENT

The first author would like to thank the Ministry of Interior (Civil Defence) in Saudi Arabia for its financial support.

REFERENCES

Abkowitz, M.D. & Chatterjee, S., 2012. Regional Disaster Risk: Assessment and Mitigation Concepts in an All-Hazards Context. *Journal of Homeland Security and Emergency Management*, 9(1).

Ajami, S. & Fattahi, M., 2009. The role of earthquake information management systems (EIMSs) in reducing destruction: A comparative study of Japan, Turkey and Iran. *Disaster Prevention and Management*, 18(2), pp.150–161.

Alsubaie, A. et al., 2013. A Platform for Disaster Response Planning with Interdependency Simulation Functionality. In *Critical Infrastructure Protection VII*. pp. 183–197.

Altay, N. & Green, W.G., 2006. OR/MS research in disaster operations management. *European Journal of Operational Research*, 175(1), pp.475–493.

Barbarosolu, G., Özdamar, L. & Çevik, A., 2002. An interactive approach for hierarchical analysis of helicopter logistics in disaster relief operations. *European Journal of Operational Research*, 140(1), pp.118–133.

Bruneau, M. et al., 2003. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, 19(4), pp.733–752.

Cimellaro, G.P., Reinhorn, A.M. & Bruneau, M., 2010. Framework for analytical quantification of disaster resilience. *Engineering Structures*, 32(11), pp.3639–3649.

Collins, T.C. et al., 2003. Integrated peer-to-peer applications for advanced emergency response systems. *Crisis*, pp.255–260.

Dillon, R.L., Liebe, R.M. & Bestafka, T., 2009. Risk-Based Decision Making for Terrorism Applications. *Risk Analysis*, 29(3), pp.321–335.

Fiedrich, F., Gehbauer, F. & Rickers, U., 2000. Optimized resource allocation for emergency response after earthquake disasters. *Safety Science*, 35(1-3), pp.41–57.

Figueras i Jove, J. et al., 2013. Simulation and optimization for an experimental environment to wildfire resource management and planning: Firefight project modelling and architecture. In *2013 Winter Simulations Conference (WSC)*. IEEE, pp. 1950–1960.

Holling, C.S., 1973. Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, 4(1), pp.1–23.

Hu, X., Sun, Y. & Ntaimo, L., 2011. DEVS-FIRE: design and application of formal discrete event wildfire spread and suppression models. *Simulation*, 88(3), pp.259–279.

Khouj, M.T., Sarkaria, S. & Marti, J.R., 2014. Decision assistance agent in real-time simulation. *International Journal of Critical Infrastructures*, 10(2), p.151.

Kondaveti, R. & Ganz, A., 2009. Decision support system for resource allocation in disaster management. *Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference*, 2009, pp.3425–3428.

Li, H. et al., 2009. Ranking the risks from multiple hazards in a small community. *Risk Analysis*, 29(3), pp.438–456.

Martí, J.R., 2014. Multisystem Simulation: Analysis of Critical Infrastructures for Disaster Response. In G. D'Agostino & A. Scala, eds. *Networks of Networks: The Last Frontier of Complexity*. Understanding Complex Systems. Cham: Springer International Publishing.

National Fire Protection Association (NFPA), 2010. *NFPA 1720: Standard for the organization and deployment of fire suppression operations, emergency medical operations, and special operations to the public by career fire departments*,

National Infrastructure Advisory council (NIAC), 2009. Critical Infrastructure Resilience Final Report and Recommendations. , pp.1–43.

Ntaimo et al., 2008. DEVS-FIRE: Towards an integrated simulation environment for surface wildfire spread and containment. *SIMULATION*, 84(4), pp.137–155.

Pant, R., Barker, K. & Zobel, C.W., 2014. Static and dynamic metrics of economic resilience for interdependent infrastructure and industry sectors. *Reliability Engineering and System Safety*, 125, pp.92–102.

Petrovic, N., Alderson, D. & Carlson, J., 2012. Dynamic resource allocation in disaster response: tradeoffs in wildfire suppression. *PloS one*, 7(4), p.e33285.

Pimm, S.L., 1984. The complexity and stability of ecosystems. *Nature*, 307(5949), pp.321–326.

Schryen, G., Rauchecker, G. & Comes, T., 2015. Resource Planning in Disaster Response. *Business & Information Systems Engineering*, 57(4), pp.243–259.

The Kuwait Finance House (KFH), 2013. *Saudi Petrochemical – Tread with Caution*, Kuwait.

Wang, K. & Marti, J., 2012. Optimal Decision Maker Algorithm for Disaster Response Management with I2Sim Applications. , (April), pp.1–5.

Waugh, W.L. & Streib, G., 2006. Collaboration and Leadership for Effective Emergency Management. *Public Administration Review*, 66(s1), pp.131–140.

Wex, F. et al., 2014. Emergency response in natural disaster management: Allocation and scheduling of rescue units. *European Journal of Operational Research*, 235(3), pp.697–708.