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Self-adaptive response system (SARS) for emergency logistics and transportation management

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Abstract

This work proposes a framework of a self-adaptive response system (SARS) for managing emergency logistics and transportation responses by integrating internal and external resources during the self-help period in the aftermath of any disaster. Accordingly, this work develops a conceptual model and discusses the model parameters required for model formulation. The multi-objective conceptual model involves four objective functions: survival maximization, casualty exposure risk minimization, undersupply cost minimization, and psychological cost minimization. This work further uses a case of Typhoon Morakot in Taiwan to identify the model parameters required for further analytical validation. Therefore, the proposed conceptual model may be important in implicating a self-organized logistics and transportation decisions during the self-help period in the aftermath of any disaster.

Keywords: Self-adaptive response system (SARS); Emergency Logistics; Emergency transporatation; Logistics resource management; Self-help; Survival Psychology; Taiwan.

1. Introduction

Large-scale and sudden-onset natural disasters often cause similar logistics problems, limiting emergency logistics management (ELM) around the affected areas, such as the 2004 ocean earthquake and tsunami in India, 2005 hurricane Katrina in USA, 2009 typhoon Morakot in Taiwan, 2012 tsunami in Japan, 2013 Typhoon Haiyan in the Philippines, 2015 Nepal earthquake and 2018 Indonesia earthquake. For example, the 2013 Typhoon Haiyan caused huge damage to infrastructure such as the debris blocked airports, roads, and other access routes, leading to delay in outside relief workers and supplies. The primary relief resources, including relief workers and supplies, must be obtained from within the affected area; external relief resources are often insufficient in meeting the

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demands due to the limited capacities of transportation modes, such as human transport, airdrop, or boat. “Self-help period” is the period from when the disaster strikes to the time that the logistics problems are solved.

Another logistics problem is ineffective disaster management among most public sector organizations. For instance, in 2013 Typhoon Haiyan, when thousands of desperate survivors mobbed a food warehouse a wall collapsed resulting in eight deaths (BBC News Asia, 2013). However, this increased death toll is not directly caused by the disaster but by the inefficient emergency disaster management inside the area.

Emergency logistics management is increasingly drawing the attention of researchers and practitioners around the globe; however, most current researches discuss issues associated with “external” logistics (Barbarosoglu et al., 2002; Chang et al., 2007; Falasca and Zobel, 2012; Fiedrich et al., 2000; Jacobson et al., 2012; Lee et al., 2009; Lodree and Taskin, 2009; Najafi et al., 2013; Ozdamar et al., 2004; Peng et al., 2014; Rawls and Turnquist, 2012; Sheu, 2007, 2010; Tzeng et al., 2007; Yi and Kumar, 2007; Sheu, 2010). Our literature review found no discussion of the issue related to “internal” logistics. Notably, previous literature discusses roles of the international or local NGOs adjacent to the affected area, and public organization, while the roles within the area are the local government offices of the area, and the local NGOs/volunteers either living or arriving in the area before the disaster occurs. The inside roles should self-organize the temporal emergency response organization, and jointly operate emergency logistics and transportation (ELT) operations during the self-help period.

This paper aims to propose a self-adaptive response system (SARS) to be applied to the organization; however, it does not discuss the coordination of such resources within the response organization. Notably, the system is used to manage the ELT operations by integrating inside relief resources in response to the post-disaster impact during the self-help period.

The rest of this paper is organized as follows: Section 2 reviews the relevant literature and presents the objectives involved in the proposed conceptual model. Section 3 introduces the framework of the proposed system. Section 4 presents a real case analysis of the Typhoon Morakot in Taiwan to identify the model parameters required for model formulation. Section 5 offers conclusions and directions for future research.

2. Related Work

Literature review related to developing a model for ELT found that the majority of studies focused on logistics costs; travel time; travel distance; operation risk; survivors; restored paths; or unsatisfied demand (Abounacer et al., 2014; Afshar and Haghani, 2012; Aksu and Ozdamar, 2014; Campbell et al., 2008; Chang et al., 2007; Daganzo and So, 2011; Jacobson et al., 2012; Li et al., 2012; Mete and Zabinsky, 2010; Najafi et al., 2013; Naji-Azimi et al., 2012; Rawls and Turnquist, 2010; Regnier, 2008; Yi and Kumar, 2007). These variables were extensively utilized in the multi-objective or single objective functions. According to the environment inside the affected area during the self-help period, the objectives related to survivors and relief-supplies distribution are fundamental concerns when developing a conceptual model for the proposed system.

Casualties found in bodies of water could contaminate it with fecal matter or with diseases that are endemic in the area (PAHO, 2004; IPCC, 2012). For example, in 1998, the severe flood in Dhaka caused an increase in diarrhea during and after the disaster (Hashizume et al., 2008). Further, persons who are in close contact with the dead-such as military personnel, rescue workers, volunteers, and others may be exposed to chronic infectious hazards (Morgan, 2004). The casualty of animals had a specific communicable disease and may pose a risk to the population (PAHO, 2004). However, casualty exposure risk is critical to emergency response, but no research discussing the ELM considers it as an objective in the model, especially in those formulated for the disasters caused by hurricanes (Li et al., 2012) and floods (Chang et al., 2007). Therefore, the proposed conceptual model identifies risk related to casualty exposure as its objective.

Further, disasters also cause serious psychological and mental harm to the affected people. Issue such as posttraumatic stress disorder (PTSD), grief, depression, anxiety, and suicidal ideation (Kinston and Rosser, 1974; Ollendick and Hoffmann, 1982) are common among the survivors. The degree of the psychological impact varies with the magnitude and circumstances of the disaster (Drayer, 1957). Lowe et al. (2013) address that stressors experienced during disasters and their immediate aftermath influence longer-term post-disaster posttraumatic stress. According to one literature review (Goldmann and Galea, 2014), the prevalence of PTSD is at 30–40% among direct victims, 10–20% among rescue workers, and 5–10% within the general population. Accordingly, the psychological impact of catastrophes cannot be ignored in the design of relief planning (Drayer, 1957). Although the psychological impact is critical to ELM, little research has considered this fact (Hu and Sheu, 2013; Sheu and Pan, 2014). For example, Sheu and Pan (2014) propose a method for designing a centralized emergency supply network, and they address objectives including travel distance, operational, and psychological costs. The proposed conceptual model formulates the psychological costs perceived by the affected people.

The distinguishing features of the proposed (SARS) system, and the contribution of this study to related areas are outlined below.

1) The proposed (SARS) system focuses on self-managing the ELT needed in the affected area by utilizing the internal resources when outside logistics are either unavailable or limited. In contrast, most of the published models address ELT issues by sourcing logistics from outside the affected areas. Moreover, such external logistics can be frequently clogged before arriving to affected areas, termed the phenomenon of “material convergence.” Therefore, ELT also requires the self-adaptive ELT mechanism built internally in the affected areas to manage logistics in the aftermath of a disaster.

2) The objective functions of the proposed model are demand-driven rather than supply-driven. Differing from most existing models, which are founded mainly on supply-driven objective functions (minimizing logistics and operation costs), ELT should aim to effectively and efficiently satisfy the urgent needs for survivor resilience. This argument may hold true particularly when addressing the issue of SARS in the affected areas. Thus, the objective functions characterized in the proposed model aim at increasing the post-disaster resilience of survivors in the affected areas.

3. Framework of the self-adaptive response system (SARS)

The proposed system applies to a sufficiently small area, such as a township or community, where the external logistics is limited or unavailable. In such an area, local government offices and NGOs, and volunteers self-organize into a fast-response organization to manage the emergency logistics operations during the self-help period at the aftermath of any disaster. The proposed system aims to develop and provide a fast-response organization for managing both internal and external relief resources in response to the impact of a disaster. Figure 1 presents the framework of the proposed system.

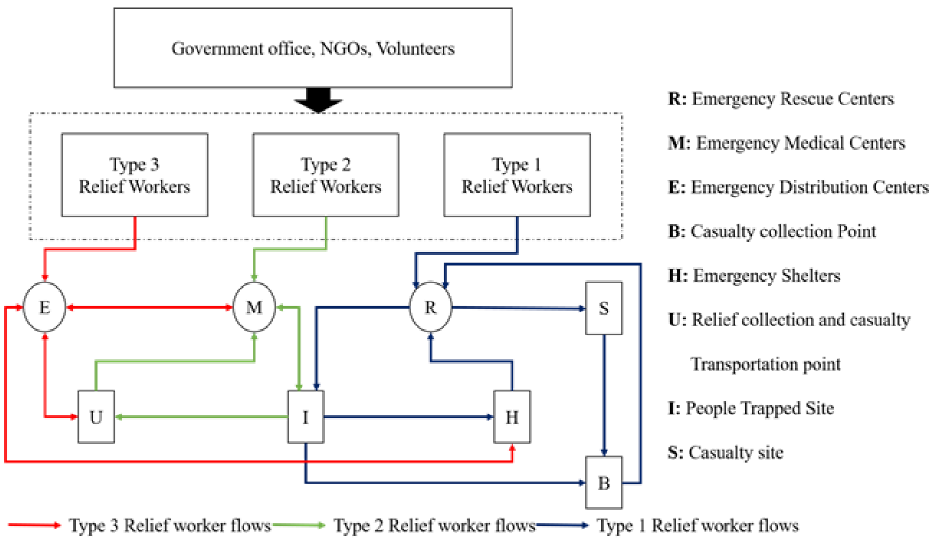

Figure 1. Framework of the Proposed (SARS) System

The system involves six emergency facilities, i.e., emergency rescue centers (R), medical centers (M), distribution centers (E), shelters (H), relief collection and casualty transportation points (U) and two demand points; people-trapped sites (I) and casualty sites (S). Notably, a casualty collection point is a site that is far from survivors and water sources, such as a farmland in a higher location to avoid disease infection and other psychological effects on the survivors. A relief collection and casualty transportation point is a large, flat area such as school playing field, which allows for helicopter landing. A people-trapped site refers to a building or confined place in the affected area.

This system classifies a member or group arriving at the emergency operation center by their characters of relief skills, such as rescue and search skills, medical treatment, and general skills. All members or groups are classified into three types of relief workers and are allocated to emergency rescue centers (R), medical centers (M), and distribution centers (E), respectively. The corresponding missions for the specific type of relief worker are as follows:

Type 1 relief workers are responsible for collecting casualties and rescuing trapped people. For casualty collection, Type 1 relief workers depart for the casualty sites and transport casualties to the casualty collection points. For rescue and search, the workers will be assigned to sites where people are trapped. When a trapped person is rescued or found, he/she will be immediately triaged according to four current-health-state categories: non-injury, slight injury, serious injury, and death. Non-injury survivors and casualties are transported to emergency shelters and casualty collection points, respectively. Type 2 relief workers transport survivors with slight or severe injuries to emergency medical centers and casualty transportation points, respectively. The primary missions of type 3 relief workers are relief supplies collection and distribution. They go to relief collection points and distribute external relief supplies back to the emergency distribution centers. The relief workers then distribute relief supplies to the emergency medical centers and shelters. Once their assignment is complete, every relief worker returns to the original centers.

The above-mentioned basic system is termed as non-reallocation system, where reallocation of relief workers is restricted. For instance, type 1 relief workers are restricted to allocate to other two emergency facilities during the period. In reality, many relief workers may have multiple relief skills, who may not only rescue and collect casualties but also provide first aid to injured survivors and distribute and collect relief supplies. For example, a community emergency response member may have several basic disaster response skills, including fire safety, light search and rescue, team organization, and disaster medical operations (FEMA, 2014). Thus, if a relief worker has multiple relief skills, he/she could be reallocated to two other emergency facilities and do the corresponding missions over different time intervals. This system is termed as reallocation system. Accordingly, a mathematical connotation concerning the proposed self-adaptive emergency logistics response system is presented. However, the current paper will not be describing the exact mathematical representation but will discuss the multi-objective functions and constraints associated with the proposed model. Further, this work makes two assumptions.

Assumption 1: The relief workers have a corresponding loading capability for conducting EL operations. To simplify the proposed programming model, a relief worker is identified as a transportation mode (e.g., boat) with the corresponding loading capacity when transporting survivors, casualties or supplies.

Assumption 2: The study assumes that families inside the area have stored commodities for the self-help period.

The proposed programming model involves four objective functions, including survivor maximization, casualty exposure risk minimization, undersupply cost and psychological cost minimizations. Accordingly, the first objective function concerning minimization as objective can be expressed as:

$$\min f = f_1 + f_2 + f_3 \tag{1}$$

where, f_1 presents the total risks caused by human and animal casualties exposure during the self-help period. f_2 presents the sum of the negative inventories of relief supplies in the emergency medical centers and survivors in the emergency shelters. f_3 denotes the total psychological cost perceived by the relief workers and survivors during the self-help period.

Similarly, the second objective function concerning maximization as the objective can be expressed as:

$$\max g = g_1 \tag{2}$$

where, g_1 presents the total cumulated survivors in the emergency facilities during the self-help period.

Hence, it can be seen that Eqs.1 and Eqs.2 represent the two main multi-objective function of conflicting objectives. Therefore, Eqs.1 and Eqs.2 can be combined to become one minimization objective function as:

$$\min h(f, -g) \tag{3}$$

The constraints are divided into four groups associated with relief workers, survivors, casualties, and relief supplies.

(1) Constraints for relief workers

The constraint for the relief workers includes the number of relief workers in their corresponding emergency facilities at time t. The constraints must ensures that the number of type 1 relief workers in an emergency rescue center, at time t, equals the number at time t-1, minus the total number leaving for the operations, plus the total number returning to and arriving at the center, plus the number of other relief workers reallocating to the center, minus the number reallocated to two others types of centers, at time t. Various binary parameters can set by the managers, according to the relief workers' skills and present whether or not the allocation function is available. For example, if type 1 relief workers in an emergency rescue center have multiple relief skills related to medical treatments and relief-supplies collection and distribution, then both binary parameters equals 1, which means that type 1 relief workers could be reallocated to emergency medical centers or emergency distribution centers.

According to the proposed system framework (Figure 1), another set of constraints may include the number of specific type relief workers acting in the emergency facilities or demand points to balance the rescue operations.

(2) Constraints for survivors

The constraints for the survivors present the number of survivors with non-injury, slight injury, and serious injury in a demand point. The proportions of health states-non-injury, minor injury, serious injury, and death-of the trapped people rescued in a time interval can be characterized in the form of a parameter where the submission of the same must be equal to one. Further, loading capacities for transporting survivors is also considered in the constraint.

(3) Constraints for casualties

The constraints for the casualties presents the casualties (human and animals), and their amounts. The loading capacities constraints for relief workers to transport casualties is also considered.

(4) Constraints for relief supplies

This constraint is a balance constraint for the quantity of relief supply in a relief-collection point, presenting that the quantity of relief resource, in a point at time t, equals the quantity at time t-1, plus the quantity of external supplies transported to a point, at time t, minus the quantity transported to emergency distribution centers at time t. Similarly, the quantity of relief supply stored in an emergency distribution center at time t can also be considered.

4. Case Analysis

A case analysis aimed at the 2009 case of Typhoon Morakot, Taiwan, is conducted to analyze the model parameters required for further investigation of the proposed conceptual model. The target of this study is Linbian township, located in the western part of Pingtung County in the southwest of Taiwan, on the coast adjacent to the Taiwan Strait (Figure 2). The area has a tropical monsoon climate and is 15.6 km^2 in size. At the end of 2013, the population density of Linbian Township was 1,510.7 people per sq. km. (Linbian Township Office, 2014).

Residents in the township suffered substantially when the massive typhoon hit the area between August 8, 2009 and August 10, 2009. The excess rain caused severe flooding throughout the area (Executive Yuan of Taiwan, 2010). This study assumes the target township suffers from the damage caused by a large typhoon. Most houses are flooded, and the outside logistics are clogged since the traffic infrastructures linking the area to the other townships are flooded. The emergency operation center is located in Linbian Township Office. The nodes involved in the affected area have one emergency rescue center, two emergency medical centers, one distribution center, four emergency shelters, one casualty-collection point, one relief collection and casualty transportation site, six people-trapped sites, and four casualty sites.

Figure 2. Case Analysis (Image Source: Google Maps)

According to the data of the historical report and the Pingtung County Government website (Pingtung County government, 2013), following parameters were identified that might contribute for the further development of SARS model.

Table 1. Identified parameter from case study

Parameter	Unit
People trapped in demand points at the initial time	Person
Casualties in casualty sites at the initial time	Person and kg
Capacities of the Shelters	Person
Medical Centers	No. of bed
Quantities of stored relief resources in Distribution Centers	kg
Quantities of outside relief supplies	kg
Casualty collection points	Person and kg
Number of relief workers in emergency facilities (constraints)	Person
Quantities of outside relief supplies transported	kg
Number of causalities in collection point at time *t*	Person
Risk function of casualty exposure	Person and kg
Urgency degree of relief supply	Numerical weight (1 and 2)
Psychological cost function	$

Since the values of the objective functions have different units, an indicator, the rate of change (ROC) can be used to determine and compare the difference between the objective values of proposed reallocation and non-reallocation systems. The ROC measures the percentage change in the objective function value from a non-reallocation system to a reallocation one. A negative value of the ROC implies a smaller objective value in the reallocation system than in non-allocation one. In contrast, a positive value of the ROC implies a greater objective value in the reallocation system than in the non-allocation one. Finally, this works proposes the following proposition. However, an analytical validation as future development work is required.

Proposition 1: The availability of the reallocation function in the system leads to an efficient assignment of relief workers, and improves the objective values.

Proposition 2: Objectives selection and combination is momentous to results of system performance. For instance, considering only two tradition objectives, undersupply cost indeed decreases, but the casualty exposure risk significantly increases.

Proposition 3: NGOs and volunteers' involvement have a significant improvement on results of self-adaptive ELT operations. No involvement of NGOs and volunteers in the operations leads to significantly slow rescue of trapped people higher psychological cost compared with volunteers' involvement.

5. Conclusion

In the aftermath of any disaster, by the time external logistics comes into action, residents trapped in the affected area have to engage in self-help. This paper proposes a novel self-adaptive response system (SARS) for managing emergency logistics and transportation operations by integrating both the internal and the limited external resources during the self-help period. Further, a case study of the target area was analyzed to identify model parameters and demonstrate the applicability and potential advantages of the proposed system.

The main contributions of this article are twofold. First, it provides a framework, for designing the SARS, which shows the directions of relief flows and emergency facilities that should be involved, especially in the potential disaster area. Second, the proposed model of the system contains not only traditional objectives (i.e., survival maximization and undersupply cost minimization) but also minimization of both casualty exposure risk and psychological cost.

According to the case analysis, several vital questions concerning the model parameters have been identified for further numerical and empirical analysis.

Great potential still exists to improve the performance of the proposed system. This study points to several areas where further research would be valuable to academics. First, design a self-adaptive emergency network for the self-help period. Second, develop a policy of distribution selection for the affected people within vulnerable states, such as children and women. Third, develop a mixed reallocation system, that is, relief workers with one, two, or three relief skills involved in a system. Fourth, various transportation mode constraints can also be considered in the model. Finally, with this study emergency managers and researchers can further develop a practical and effective system for related issues in the future.

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