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A Multi-district Asset Protection Problem with Time Windows for Disaster Management

S. Kazazi Darani, M. Bashiri*

Department of Industrial Engineering, Shahed University, Teheran, Iran

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ABSTRACT

One of the most important goals of disaster management teams is to protect the assets and infrastructures of the community in the event of accidents such as wildfires and floods. This issue requires appropriate operations of all disaster management teams and analysis of available information for suitable decision making and consequently timely response. A mixed integer mathematical model is presented and solved for allocating resources to different districts to protect more assets in an available time. The proposed model tries to protect more valuable assets in pre-determined districts with optimized team allocation strategy. Finally, for validating the model, a numerical example is solved with an exact method and the results of various sensitivity analyses have been reported. The computational results indicate the efficiency and applicability of the proposed model in real conditions comparing to existing classic models.

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1. INTRODUCTION

In case of occurring a wildfire in populated areas, it will cause a lot of physical and financial loss to personal property and community assets. In many countries, incident management teams are responsible for coordinating, planning and managing response and reaction activities at the time of the disaster; which must be made in accordance with the complexity of critical circumstances in current situation. One of the tasks of these teams at the time of the incident include: assessing available information, devising relief strategies, minimizing destructive effects, managing relief protection groups and other existing resources; finally issuing warnings to public and evacuation of people. The factors affecting decision making include: climate conditions, predictions, fuel status, threatened assets, assets' values and vulnerable locations [1-3]. A disaster consists of four major phases: mitigation, preparedness, response and recovery; which are always interconnected and overlapping. In the mitigation phase, the goal is to prevent emergencies and to minimize their effects. In the preparedness phase, the goal is to prepare for emergencies and include pre-determined plans to deal with the disaster. In the response phase as a reaction to emergency condition, it is tried to save lives and prevent further damages during the incident. Finally, in the recovery phase, conditions must be returned to the normal status [4-6].

In this paper, the proposed routing-based model for protecting assets in response phase is presented. During a crisis, evacuation and relief operations are important subjects in order to preserve lives and prevent harmful injuries based on preplanned preparedness decisions. High percentage of incident damages is attributed to devastate of community infrastructures, so protection of basic assets may be considered as another important reaction during a response phase. It is clear that in the recovery phase, many of these assets play a key role in restoring society to a desirable normal status. There are only few studies in the community assets protection during a response phase of a disaster. In this paper, the issue of allocating resources for asset protection activities is considered when a critical and uncontrollable disaster occurs, also routing the selected points will be a part of a decision, too. Here a mathematical model with the objective function of

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*Corresponding Author Email: *bashiri@shahed.ac.ir* (M. Bashiri)

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maximizing scores derived from protected assets is presented. Most of previous studies have considered special conditions to get closer to the real world situations such as assets protection time windows, resource constraints, various types of relief vehicles with different abilities. The main contribution of this study is considering multi-districting strategy to increase the protection efficiency. A region is divided into several districts, each of which individually has two depots. The first depot is intended to start teams moving in order to visit and protect assets and the other one (docking depot) for servicing teams and maintaining their tools.

Remainder of this paper is organized as follows: in the next section, the literature review and the studies conducted in this field are discussed. Then, the asset protection problem and its issues that used in this study are illustrated. The proposed mathematical model is introduced in section 4. In section 5, the computational results of the paper and sensitivity analyses are reported. Finally, the conclusion and suggestions for future studies are presented in the last section.

2. LITERATURE REVIEW

Here, the present study addresses disaster management in the response phase, so we will focus on related studies of the response phase in this part. Main activities of this phase include evacuation of affected people, activating of the emergency operations centers, emergency rescue and curative care, management of fatalities, fire fighting, and protection of community assets.

According to Table 1, it can be concluded that there are a few researches on asset protection as an activity during a response phase while there is no study on asset protection that uses districting to improve response phase activities efficiency. Because of importance and necessity of efficiency improvement of response phase activities during a disaster, here we consider the asset protection with the presence of districting possibility.

3. PROBLEM STATEMENT

Protecting assets and key infrastructures is one of the most important goals of incident management teams. One of the operation in response to emergencies is the asset protection. Asset protection operation includes all actions should be performed to ensure the safety of the individuals, equipment and the environment during a disaster to reduce risks in an acceptable level. For example, in the response phase, the priority is fire controlling, but due to time constraints, lack of resources and high volume of fire, it is possible to protect some of the assets.

TABLE 1. A Summary on Related Researches

Related Activities	**Disaster Type**			**Special Features**			**Solution Approach**			**Papers**
	Wildfire	Earthquake	Flood	Time Windows	Resource limitation	Multi districting	Exact	Heuristic	Metaheuristic	
Evacuation					✓			✓		Dhingra, and Roy [7]
Evacuation		✓		✓	✓				✓	Pourrahmani et al. [8]
Evacuation			✓		✓				✓	Gama et al. [9]
Fire Fighting					✓				✓	Krentowski [10]
Fire Fighting	✓				✓			✓		Zhang et al. [11]
Emergency Rescue					✓			✓		Zhao and Chen [12]
Emergency Rescue		✓			✓				✓	Huang et al. [13]
Emergency Rescue			✓		✓				✓	Yang et al. [14]
Asset Protection	✓			✓	✓		✓			Van der Merwe et al. [15]
Asset Protection					✓			✓		Roozbeh et al. [16]
Asset Protection	✓			✓			✓			Van der Merwe et al. [15]
Asset Protection				✓	✓	✓	✓			Current research

Therefore, the necessity of using asset protection increases when the severity of the disaster is more than the system's ability to extinguish the fire. Urban facilities, especially bridges, hospitals, schools, ancient and historical relics, factories, commercial towers, facilities and main lines of water, gas, sewage and electricity transmission lines are among the most important assets of a community.

In the asset protection problem, when an incident occurs, there is not enough time to protect all assets. In addition, these assets have different values determined based on their importance. Therefore, the relief management teams determine the optimal sequence for visiting assets by considering extent of the calamity and available time. For this purpose, at first asset values are defined based on the decision marking groups' opinions. The impact of asset in the recovery of community after the disaster is one of the important factors for determining values. It is assumed that the problem of asset protection has the routing and asset selectivity substance, the presented problem has some common aspects to the classic travelling salesman problem with time windows. Other important issues are the distribution and placement of assets in different zones, so mutli-districts are defined before a disaster. The zone division is done for better management as well as ease of protection of assets. The results and sensitivity analysis of this districting will be described in the following sections. Figures 1 and 2 show an instance of single-district and multi-district asset protection actions, respectively. In this example, it is observed that the number of protected assets in the multi-district problem will be significantly greater than the single-district problem.

4. MODEL FORMULATION

In this section the developed mathematical model, including indices, parameters and variables are introduced as follows:

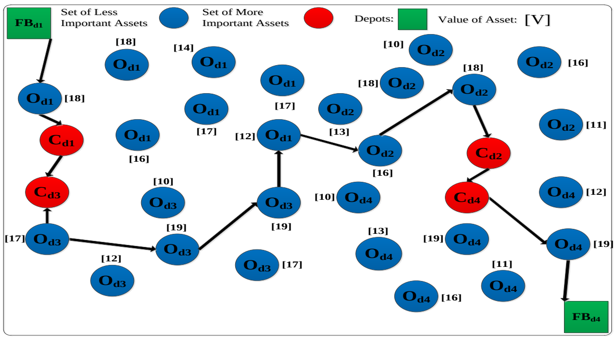

Figure 1. An example of the single-district asset protection actions

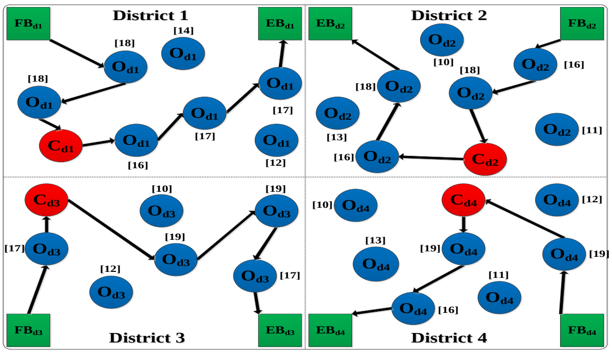

Figure 2. An example of the multi-district asset protection actions

Indices

i, j, k	Indices of potential assets
d	Index of districts
fb_d	Index of starting depot in district *d*
eb_d	Index of docking depot in district *d*
O_d	Sets of less important assets
C_d	Sets of more important assets should be protected

Parameters

V_i	Value of *i*th asset
T_{ij}	Travelling time between *i*th and *j*th assets
A_i^d	Operation time of *i*th asset in *d*th district
e_i^d	Earliest time for operating of *i*th asset in *d*th district
l_i^d	Latest time for operating of *i*th asset in *d*th district
IMT	Number of available incident management teams
M	An arbitrary large number

Decision Variables

X_{ij}^d	1 if a team is travelling from asset i to asset j in district d, otherwise 0
Y_i^d	1 if *i*th asset in *d*th districts protected, otherwise 0
IMT_d	The number of incident management teams assigned to *d*th district
S_i^d	The starting time of operating at *i*th asset in *d*th district

Mathematical Model

$$Max\ Z = \sum_{d\in D}\sum_{i\in O_d} V_i Y_i^d \tag{1}$$

Subject to

$$\sum_{i\in N_d\setminus\{fb_d\}} X_{fb_d i}^d \le IMT_d \qquad d\in D,\ fb_d\in N_d \tag{2}$$

$$\sum_{i \in N_d \setminus \{eb_d\}} X^{d}_{ieb_d} \le IMT_d \qquad d \in D, eb_d \in N_d \qquad (3)$$

$$Y^{d}_{k} = 1 \qquad d \in D, k \in C_d \qquad (4)$$

$$Y^{d}_{k} \le 1 \qquad d \in D, k \in O_d \qquad (5)$$

$$\sum_{i \in N_d \setminus \{eb_d\}} X^{d}_{ik} = Y^{d}_{k} \qquad d \in D, k \in O_d \cup C_d \qquad (6)$$

$$\sum_{i \in N_d \setminus \{fb_d\}} X^{d}_{ki} = Y^{d}_{k} \qquad d \in D, k \in O_d \cup C_d \qquad (7)$$

$$\sum_{d \in D} IMT_d = IMT \qquad (8)$$

$$S^{d}_{i} + T_{ij} + A^{d}_{i} - S^{d}_{j} \le M(1 - X^{d}_{ij}) \qquad d \in D, (i,j) \in N_d \qquad (9)$$

$$e^{d}_{i} \le S^{d}_{i} \qquad d \in D, i \in N_d \qquad (10)$$

$$S^{d}_{i} \le l^{d}_{i} \qquad d \in D, i \in N_d \qquad (11)$$

$$X^{d}_{ij}, \in \{0,1\} \qquad d \in D, (i,j) \in N_d \qquad (12)$$

$$Y^{d}_{i} \in \{0,1\} \qquad d \in D, i \in N_d \qquad (13)$$

$$IMT_d \in \{0,1,\ldots,IMT\} \quad d \in D \qquad (14)$$

$$S^{d}_{i} \ge 0 \quad d \in D, i \in N_d \qquad (15)$$

The objective function (1) represents the maximum value that is obtained from protected assets. Constraints (2) and (3) state that each route starts and ends at the depot and the number of routes does not exceed the maximum number of teams assigned to each district. Constraint (4) guarantees that each more important asset (MIA) is protected. Constraint (5) ensures that a less important asset (LIA) is selected at most once in case of time availability. Constraints (6) and (7), enforce the flow conservation conditions at the asset. Constraint (8) limits available time for incident management teams. Constraint (9) ensures that an operation in a node may only start after completing of the protection activity at previously visited asset in case of time availability. The start times of assets protection are limited to their respective time windows by constraints (10) and (11). Constraints (12) to (15) define types of variables.

5. COMPUTATIONAL RESULTS AND SENSITIVITY ANALYSIS

In this part, results of computational study for the proposed model are presented using a numerical example. In this example regarding the multi districting possibility, 64 assets were considered with their predetermined values, necessary protection requirements, duration of protection operations, and time windows for each asset. These locations were divided into four districts. There were two stations (depots) in each district. Relief teams start their protecting tours from the first station and the final station is used for teams' recovery. A sensitivity analysis is done under different number of districts, scores, relief teams to show the validity of the proposed model. Also, the effects of different values of time window were examined. The results were computed by the GAMS 24.1 optimization software.

In Table 2, the validity of the proposed model is shown for various instances by considering different combination of parameters including problem size (small, medium and large sizes), type of assets' time window (normal and tight time windows), number of districts (2, 4, 6 and 8 districts) and number of more important assets (MIA). It is assumed that, at the normal conditions, almost 20% of assets are in MIA set and must be protected. While, in the more critical conditions with tight time windows, about 30-40% of assets are considered as components of MIA set.

In Table 2, PTPA is defined as percent of total protected assets and calculated by Equation (16).

PTPA = (LIA + MIA) / Total Number of assets (16)

The results show that PTPA increased by increasing in the number of districts until 6 districts. While, PTPA values decrease in most cases by considering more than 6 districts. Therefore, it is concluded that the proposed model has good performance in 4 and 6 districts.

Different Time windows states are considered for examining the effect of time windows on asset protection scheme. Tight, normal and loose are three states of the time window.

Figure 3 illustrates that the number of protected assets is increased in cases with least emergency, so in cases with less available protecting time, less assets may be protected.

The last analysis is about the number of teams assigned to each district by considering different scores for each asset. To this end, the target region has been divided into 8 districts (A-H), and five different values for scores are defined and results are shown in Figure 4. In the first case (S1), equal scores are considered for all assets in each district and the number of teams assigned to each district is specified. Then, in the next steps, scores of nodes in districts 2, 4, and 6 are incremented successively.

TABLE 2. Protected Assets under Districting, Normal and Tight Time Windows

	Instances	Protected Assets		PTPA
		LIA	MIA	
Number of Assets:22	2D22A17L05M-N1*	04	05	41%
	2D22A14L08M-T1	00	08	36%
	4D22A17L05M-N1	09	05	**64%**
	4D22A14L08M-T1	03	08	**50%**
	6D22A17L05M-N1	07	05	**55%**
	6D22A14L08M-T1	03	08	**50%**
	8D22A17L05M-N1	04	05	41%
	8D22A14L08M-T1	01	08	41%
Number of Assets:40	2D40A32L08M-N2	04	08	30%
	2D40A27L13M-T2	00	13	33%
	4D40A32L08M-N2	07	08	**38%**
	4D40A27L13M-T2	03	13	**40%**
	6D40A32L08M-N2	10	08	**45%**
	6D40A27L13M-T2	04	13	**43%**
	8D40A32L08M-N2	08	08	**40%**
	8D40A27L13M-T2	01	13	35%
Number of Assets:64	2D64A50L14M-N3	14	14	44%
	2D64A44L20M-T3	04	20	38%
	4D64A50L14M-N3	26	14	**63%**
	4D64A44L20M-T3	13	20	**52%**
	6D64A50L14M-N3	30	14	**69%**
	6D64A44L20M-T3	13	20	**52%**
	8D64A50L14M-N3	18	14	**50%**
	8D64A44L20M-T3	09	20	45%

***2D22A17L05M-N1:** **2D:** 2 Districts**; 22A:** 22 Assets**; 17L:** 17 Less important Assets; **05M:**5 More Important Assets; **N1:** Normal Time window in Condition1 and **T1:** Tight Time window in Condition1.

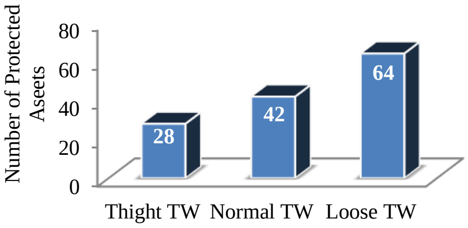

Figure 3. The effect of time window states on the number of protected asset

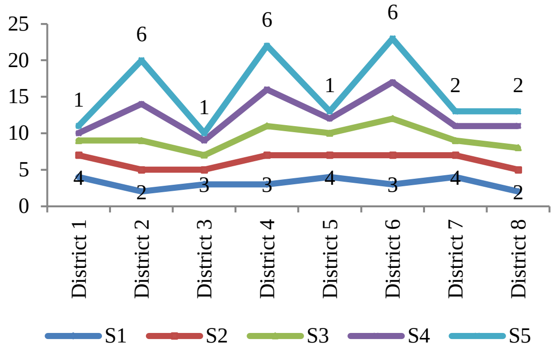

Figure 4. The effect of changing assets scores on the number of teams assigned to each district at different states

Result shows an increase in the number of teams assigned to these three districts, which also shows the validity of the proposed model.

6. CONCOLUSION

In this paper, a mixed integer-programming model was proposed for the protection of assets in occurrence of natural or man-made disasters. The goal is to help disaster management teams to use their ability to mitigate the effects of a disaster. The proposed model is an extension of the orienteering problem, with considering the multi-district concept. Testing the mathematical model shows that this model can be used for asset protection problems in real-world situations. It was concluded that by dividing a zone to several districts and then assigning protective teams to them, it has seen that the number of protected assets will be more than the single-district condition. Therefore, managers and authorities in different organizations such as Department of Environment and Emergencies, by considering this matter may use models based on multi-district asset protection for better managing of relief-protective teams. As another managerial insight, it can be concluded that the major decision in emergency relief services, districting is very important and has a high significant impact. However, we know that by increasing the size of the problem and increasing the number of assets, the solving of the model will become much more difficult, requiring the use of heuristics and metaheuristic algorithms. For future research in this area, modifications can be made such as assets semi protection due to lack of resources. Considering time windows, constraints as well as considering the problem with more objectives can be as a future work of this study.

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S. Kazazi Darani, M. Bashiri

Department of Industrial Engineering, Shahed University, Teheran, Iran

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چکیده

یکی از مهم‌ترین اهداف تیم‌های مدیریت عملیات بحران، مسئله‌ی محافظت از دارایی‌ها و زیربناهای مهم و اساسی جامعه در هنگام وقوع حوادثی مانند آتش سوزی و سیل است. این امر خود نیازمند عملکرد مطلوب و صحیح همه اجزاء مدیریت بحران و آنالیز صحیح اطلاعات موجود و داده‌های ورودی جهت تصمیم‌گیری درست و در نتیجه واکنش مناسب می‌باشد. در این مقاله، یک مدل ریاضی به‌منظور کمک به تیم‌ها در جهت تخصیص بهتر منابع برای فعالیت‌های حفاظتی و کاهش خسارات وارد آمده در طول حوادث طبیعی و یا انسان‌ساخت، توسعه داده‌شده است. مدل ریاضی عدد صحیح مختلط برای تخصیص منابع به نواحی مختلف به منظور محافظت از تعداد بیشتری از دارایی ها با توجه به زمان در دسترس ارائه و حل‌شده است. مدل پیشنهادی با توجه به استراتژی تخصیص بهینه تیم‌های امدادی به نواحی از پیش تعیین شده، سعی بر حداکثر کردن تعداد دارایی‌های محافظت شده دارد. در انتها جهت اعتبارسنجی مدل ارائه‌شده، یک مثال عددی با روش دقیق حل‌شده و نتایج حاصل از تحلیل حساسیت‌های مختلف گزارش‌شده است. نتایج محاسباتی نشان دهنده کارآیی و کاربردی بودن مدل ارائه شده در شرایط واقعی در مقایسه با مدل‌های کلاسیک است.

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