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Optimized resource allocation for emergency response after earthquake disasters

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Abstract

The main goal of the initial search-and-rescue period after strong earthquakes is to minimize the total number of fatalities. One important difficulty arising in this period is to find the best assignment of available resources to operational areas. For this problem a dynamic optimization model is introduced. The model uses detailed descriptions of the operational areas and of the available resources to calculate the resource performance and efficiency for different tasks related to the response. An adequate solution method for the model is presented as well. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Natural disasters like earthquakes often cause a high degree of damage. Especially in highly inhabited areas, thousands of people may be affected or killed. One important aspect, which helps determine the total number of fatalities after an earthquake, is the performance of search-and-rescue (SAR) in the first few days. The quality of the relief efforts can be improved by an effective use of the available technical resources. Because time, quantity and quality of the resources are limiting factors, emergency managers do have to find an optimal schedule for assigning resources in space and time to the affected areas. But because of the difficulty in assessing and processing all incoming information in an adequate manner this problem is hard to solve. Improvement can result by using computer-based decision-support systems. In this paper a mathematical model allowing for calculation of an optimized resource schedule is presented to help answer this question.

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2. Literature review

A review of the literature for appropriate models shows that similar resource allocation problems have been discussed quite rarely. Existing so-called disaster management systems usually are mere information systems, which are used for graphical presentation of disaster-relevant data. In this context geographical information systems (GIS) are getting more and more important. So far GIS-based mapping systems have mainly been used for the development of damage and loss scenarios in earthquake-prone areas (see Earthquake Spectra, 1997 and National Institute of Building Science, 1997, for different applications). The use of GIS for improvements in disaster response, like analysis of transportation lifelines, resource mapping or identification of areas with high degrees of damage, is described in Topping (1995) and Basoz and Kiremidjian (1998). Furthermore, emergency response agencies use database systems like, for example, SUMA (Pan American Health Organisation, 1999), to classify the available resources. But all these systems do not allow the next and more important step, namely active decision support by providing an optimized schedule for the available resources to the areas requesting help.

In the field of Operations Research similar problems can be found in the class of scheduling problems. One classical application is the calculation of time-tables. Dige and Lund (1993) use the heuristics Simulated Annealing to solve this problem. The most similar problem to the resource allocation problem after strong earthquakes is the machine scheduling problem. This form of scheduling problem is described in Operations Research books (e.g. Neumann and Morlock, 1993). In the classical form a number of known jobs has to be assigned to different available machines, such that the calculated schedule leads to minimal costs. More general forms of the machine scheduling problems (open-shop-, flow-shop and job-shop-problems) allow that a single job may consist of more than one sub-job on different machines. In job-shop-problems the machines working on a certain sub-job have to be known in advance.

Some published machine scheduling and project planning models (e.g. Brinkmann, 1992; Moser, 1993; Krüger et al., 1996; Lee and Kim, 1996; Neumann and Zimmermann, 1996) have obvious similarities with the described problem, but they cannot be adopted to the specific conditions arising from the threat of an earthquake. Two of the most relevant reasons for this are that transportation times of the resources from and to the demand points are neglected and that parallel use of resources does not lead to an efficiency improvement. Therefore a new and more adequate model has to be developed.

3. Relevant components

3.1. Area classification

For model building the disaster area is restricted to the most important areas which influence the number of fatalities. Fatalities which are not a direct result of primary damages are a result of delayed rescue, of a lacking medical treatment or of secondary disasters. Looking in a little more detail at the different work tasks which influence the number of fatalities, it can be seen that following three work tasks also impact the number of fatalities:

1. SAR work to rescue people out of collapsed buildings;
2. stabilizing work to prevent secondary disasters (e.g. dam failures, fire, etc.); and
3. immediate rehabilitation of the transportation lifelines to improve the accessibility of relevant areas, such as hospitals, SAR areas or potential secondary disaster areas.

This leads directly to the following breakdown of the operational areas:

1. *SAR areas* — The set $\mathcal{SA} := \{sa_1, \ \ldots, sa_{n_{\mathrm{SA}}}\}$ defines the SAR areas. These locations are places with trapped persons. Depending on the workload, we can distinguish between spontaneous SAR, light SAR, intensive SAR, and heavy urban rescue (e.g. Office for US Foreign Disaster Assistance, Agency for International Development, 1988). In our model we only consider light and intensive SAR as well as heavy urban rescue, where specialized teams and equipment are needed. Spontaneous SAR work is characterized by the emergence of on-the-spot citizen rescue groups. Although these groups perform the majority of the rescues, they are neglected in the model, because this work can hardly be influenced and coordinated.
2. *Stabilizing areas* — The set $\mathcal{TA} := \{ta_1, \ \ldots, ta_{n_{\mathrm{TA}}}\}$ defines the stabilizing areas. At these places people are endangered by secondary disasters, e.g. damaged dams or damaged buildings with high risk of collapse. If possible the population has to be evacuated out of these areas and further work to prevent the secondary disaster has to be initiated. It has to be considered that the probability for secondary disasters may be variable in time and that work at the potential secondary disaster sites decreases the related failure probability. For the model it is assumed that the failure probability decreases proportional to the executed stabilizing work. So far only stabilizing areas are considered where construction machines and equipment can be used. Other potential hazards like fire, chemical or nuclear accidents are not included in the model, because special equipment is needed for the related work tasks.
3. *Immediate rehabilitation areas* — The set $\mathcal{RA} := \{ra_1, \ \ldots, ra_{n_{\mathrm{RA}}}\}$ defines the immediate rehabilitation areas. These are locations where the road infrastructure has to be repaired well enough to allow access to other important areas, like hospitals, and to improve transportation times. For the modeling it is assumed that standard construction machines and procedures can be used for this work.

The entirety of all operational areas $\mathcal{OA}$ can be summarized in the set:

$$\mathcal{OA} = \mathcal{SA} \cup \mathcal{TA} \cup \mathcal{RA}.$$

In addition to the operational areas there are other important areas which are relevant for disaster response. These are as follows:

1. *Depots* — The set $\mathcal{DP} := \{dp_1, \ \ldots, dp_{n_{\mathrm{DP}}}\}$ defines the available depots at the disaster site. Depots are locations with resources which can be used in emergency response measures. These may include depots with SAR equipment, barracks, airports and other places where additional resources may arrive as well as operational areas where the resources finished their work and can be re-assigned to other areas.
2. *Hospitals* — The set $\mathcal{HP} := \{hp_1, \ \ldots, hp_{n_{\mathrm{HP}}}\}$ defines the available hospitals at the disaster site. In the model hospitals are defined as locations for medical treatment of the injured. In addition to the local hospitals of the affected area this includes temporary emergency hospitals and casualty collection points. The most important parameter is the number of injured persons who can be assigned to each hospital.
3. *Crossroads* — The set $\mathcal{CR} := \{cr_1, \ \ldots, cr_{n_{\mathrm{CR}}}\}$ defines the crossroads of the traffic infrastructure. Crossroads do not have a specific function for emergency response measures but they are important for the calculation of the shortest paths for the resources from a depot to an operational area.

Fig. 1 shows how the different types of locations and the related work tasks are linked together in the model ALLOCATE.

3.2. Resources

In the model ALLOCATE, resources are defined as the machines and equipment which can be used to work at the three different operational areas. It is assumed that

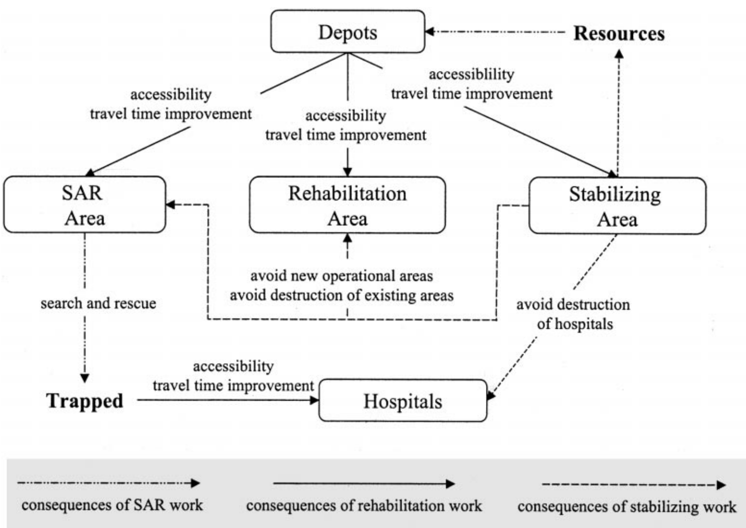

Fig. 1. Relation between area types.

all considered resources must be ready for action. Necessary staff and operating materials must be available. The set:

$$\mathcal{EWC} = \{\text{r, li, lo, t, sp, c}\}$$

$$\mathcal{EWC} = \{\text{rescue, lift, load, transport, spread, compact}\},$$

defines the six elementary work classes (EWCs) which can be used to describe all upcoming work. The quantity of work at a specific site can now be seen as a sub-set of these six tasks. Resources can be classified according to their ability to perform the different EWCs (compare Fig. 2). To ensure that the resources move only on appropriate streets, all resources have to be specified according to their ability to move on different types of roads. The considered types of resources are listed in Fig. 3. For a more detailed look on the resources, the calculation of the performance and their suitability for the different EWCs, see Rickers (1998).

3.3. The time factor

The main influencing factor for optimizing resource allocation in disaster response is time. The reason for this is the time limit of the SAR period, conditional on the

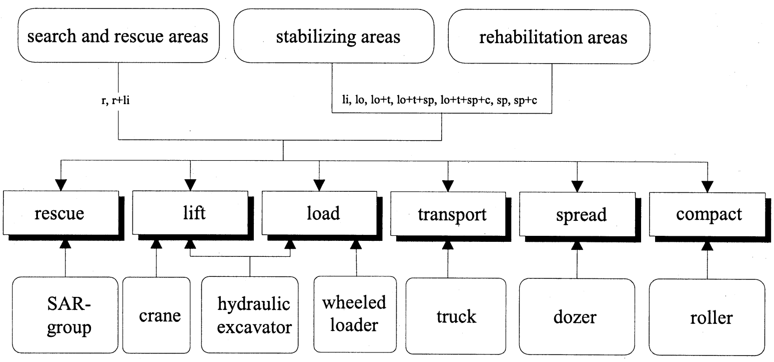

Fig. 2. Elementary work classes and the corresponding resources.

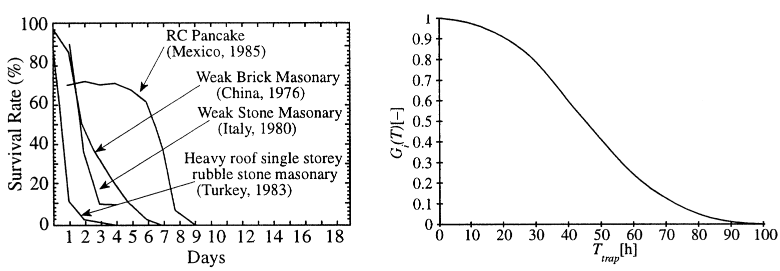

Fig. 3. Real and estimated survival rate (left picture taken from Coburn et al., 1991).

goal to minimize the total number of fatalities. In this context the following influencing parameters seem to be the most relevant ones and therefore they are used in the model ALLOCATE:

1. *Survival rate for trapped victims* — For trapped persons the probability of surviving decreases in time and depends on the physical condition and type of injuries (Shiono and Krimgold, 1989). Because these factors are usually not known before the persons are rescued, the model deals with an average probability of surviving. This probability has been recorded for several earthquake disasters and is published, for example, in Coburn et al. (1991) or Kawata (1995). In addition to the individual state of health, the parameters climate and structure of the collapsed building play an important role in this context. Usually the maximum time of surviving lies between 4 and 7 days. In the model ALLOCATE an exponential function is used to represent the survival probability function $G(T)$, because this shape is close to the published data (compare Fig. 3).
2. *Probability of secondary disasters* — The expected number of fatalities due to secondary disasters can be calculated by multiplying the failure probability of the stabilizing area by the number of people in the affected zone at a given time. Both parameters depend critically on the factor time. The function $F(T)$ for the failure probability in time is hard to calculate and due to the uniqueness of each stabilizing area $F(T)$ has to be estimated individually by experts. To test the model the authors employ the Weibull distribution, because this class of distribution is often used to describe material fatigue or failure probabilities of electronic and mechanical components. The number of persons in the endangered area is time dependent as well and corresponding evacuation functions can be estimated.
3. *Survival rate of rescued persons without medical treatment* — Since the number of medical resources is limited after a disaster, priorities have to be determined. The army and the civil protection use a casualty breakdown by injury severity level defined by a four-level injury severity scale with the classes S1, S2, S3 and S4. For a detailed description of these classes see, for example, Coburn and Spence (1992). The model takes the classes S2 (injuries requiring a greater degree of medical care), S3 (injuries which pose an immediate life-threatening condition if not treated adequately) and S4 (instantaneously killed or mortally injured) into consideration, where the persons in S4 are added to the death rate immediately. To calculate the number of victims requiring hospitalization the classes S2 and S3 are merged in the single class S2. On average the probability of surviving decreases to zero during one day, where a s-shaped form can be assumed (BMI, 1991).
4. *Transportation time* — Usually the resources are not kept directly at the places where they are needed and therefore long transportation times may occur. Shortest-path-algorithms are used to compute the best paths depending on the attributes of the resources and the network.
5. *Time to complete the work* — Depending on the given quantity of work and on the efficiency of the available resources, the time to complete the work tasks

can be calculated with the help of the breakdown into six elementary work classes.

The model assumes that the SAR period is over if the three following conditions hold:

1. all trapped persons in the SAR areas are rescued or the probability for surviving equals zero;
2. the work at all stabilizing areas is completed or there are no more persons in the according danger zones; and
3. all hospitals are reachable or there are no more injured persons without sufficient medical treatment in injury class S2.

Because the duration of the SAR period depends directly on the chosen resource schedule, it is not a predefined parameter. The states of the system change in time and therefore they have to be included in the decision process. The expected number of fatalities has to be recalculated each time the state of the system changes. Therefore, the SAR period $[T^0, T^{\text{end}}]$ is split into non-equidistant time intervals as:

$$[T^0, T^{\text{end}}] = [T^0, T^1] \cup (T^1, T^2] \cup \ldots \cup (T^{\text{end}-1}, T^{\text{end}}].$$

The non-equidistant time intervals do not have a predefined length, but their length depends on system changing events. These discrete events occur if:

1. resources arrive at an operational area;
2. resources finish work at an operational area; or
3. a secondary disaster occurs due to the failure of a stabilizing area.

4. The model ALLOCATE

4.1. Representation of the disaster area

In its abstract form the disaster area can be represented by an undirected graph $G = [V, E]$, where V is the set of vertices and E the set of edges. The nodes symbolize important locations and are composed of the areas described in Section 3.1. The edges represent the links between the nodes (compare Fig. 4). Each type of vertex has a detailed attribute list concerning its specification, e.g. a depot is specified by the resources located at this depot. The edges describe the underlying road network. To ensure that only allowable resources move on the roads an edge e is defined by the attribute set a with:

$$a = \{\text{length, max. speed, max. weight, max. width, max. height, grade, acceleration factor}\}.$$

During the calculation of the optimal allocation of the resources the graph is subject to variations. Completed areas are no longer required and corresponding

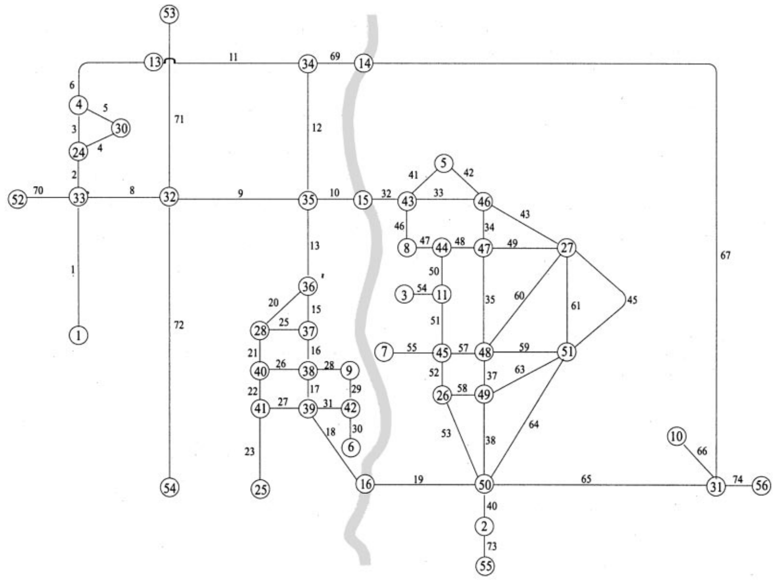

Fig. 4. Network representation of fictitious test area.

nodes can be removed from the graph. Because the locations of the resources are not fixed during emergency response, the set of depots varies in time. On the other side secondary disasters may lead to new nodes. Nodes and edges which are totally destroyed can be removed from the graph as well. Due to potential damages of the traffic lifelines it is possible that the graph G may be decomposed into two or more independent subgraphs $G_1, \ldots, G_n$ which have no connecting edges.

4.2. Components of the goal function

A policy π may define the exact schedule for all resources during the complete SAR period. For each policy π the expected length of the SAR period $[T^0, T^{\text{end}}]$ and the expected value for the total number of fatalities $f(\pi)$ at the end of the SAR period can be calculated, where $f(\pi)$ represents the goal function of the model, which should be minimized. The policy π which leads to the minimal value of $f(\pi)$ represents the solution of the model and is the best available schedule. For each policy π we can calculate $f(\pi)$ by summing up the corresponding expected values of fatalities for all causes of death over all relevant time intervals.

The next paragraphs briefly describe the calculation of the expected number of fatalities for the different causes of death.

4.2.1. Fatalities due to secondary disasters

Stabilizing areas have a failure probability varying in time and depending on the work undertaken to prevent the secondary disaster. It is assumed that this probability can be determined for each stabilizing area i. The failure probability may follow the distribution $F_i(T)$ and the density $f_i(T)$. Work at a stabilizing area decreases the failure probability proportional to the executed stabilizing work and therefore $F_i(T)$ is shifted to $F_{v,i}(T)$ (Fig. 5).

The possible number of fatalities can be estimated by summing up the expected values for the number of fatalities per time interval. The failure probability $\hat{p}_i$ of a stabilizing area in time interval ($T^{\mathrm{m}-1}$, T^m) equals the difference of the absolute failure probabilities at the boundaries of the time interval. The variable $\hat{p}_i$ can be estimated by:

$$\hat{p}_i = F_i(T^m) - F_i(T^{m-1}), \ \forall i \in \mathcal{TA}.$$

To calculate the number of fatalities $X_{1,i}(T^m)$ in a stabilizing area i by time interval (T^{m-1}, T^m), the failure probability has to be multiplied by the average number of people $N_i(T^m)$ staying in the endangered area and by the probability α_i^{killed} of being killed. Additionally the percentage of the completed work has to be considered. This part can be estimated by:

$$\hat{q}_i = \frac{V_{\text{rest},i}(T^{m-1}) + V_{\text{rest},i}(T^m)}{2V_i^0}, \ \forall i \in \mathcal{TA},$$

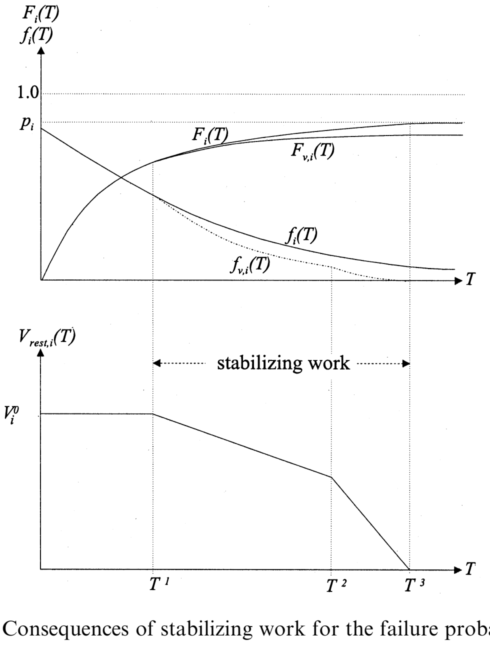

Fig. 5. Consequences of stabilizing work for the failure probability.

where $V_{\text{rest},i}(T^{m-1})$ and $V_{\text{rest},i}(T^m)$ represent the remaining workload of stabilizing area i in the corresponding time step. So we can calculate the total number of fatalities due to secondary disasters in (T^{m-1}, T^m) as follows:

$$X_1(T^m) = \sum_{i \in \mathcal{TA}} X_{1,i}(T^m)$$

$$X_1(T^m) = \sum_{i \in \mathcal{TA}} \hat{p}_i \hat{q}_i \alpha_i^{\text{killed}} N_i(T^m).$$

For further considerations in Section 4.2.4 we have to determine the number of persons being in injury class S2 as well. This can be calculated in an analogous way:

$$X_{1,i}^{\text{S2}}(T^m) = \hat{p}_i \hat{q}_i \alpha_i^{\text{S2}} N_i(T^m), \ \forall i \in \mathcal{TA}.$$

4.2.2. Fatalities due to duration of the rescue operation

The number of these fatalities has to be calculated separately for each SAR area $i \in \mathcal{SA}$. An SAR area i is specified by the initial number of victims n_i^0 and the total initial workload V_i^0 which has to be removed or lifted to rescue all trapped persons. If we want to calculate the average number of people $\Delta n_i(T^m)$ being rescued in time interval (T^{m-1}, T^m) we have to calculate the performance P_i of the assigned resources. For a detailed look at the calculation of resource performance see Rickers (1998). With this information $\Delta n_i(T^m)$ can be estimated:

$$\Delta n_i(T^m) = \frac{P_i}{V_i^0} n_i^0 (T^m - T^{m-1}), \quad \forall i \in \mathcal{SA}.$$

Under the assumption that on average the victims are rescued in the middle of time interval (T^{m-1}, T^m), by using a function $G_i(T)$ for the probability of surviving over time, the number of persons rescued alive $X_{2,i}^{\text{alive}}(T^m)$ and dead $X_{2,i}^{\text{killed}}(T^m)$ can be calculated for each SAR area by:

$$X_{2,i}^{\text{alive}}(T^m) = G_i(0.5T^{m-1} + 0.5T^m)\Delta n_i(T^m), \quad \forall i \in \mathcal{SA}, \quad \text{and}$$

$$X_{2,i}^{\text{killed}}(T^m) = \Delta n_i(T^m) - X_{2,i}^{\text{alive}}(T^m), \quad \forall i \in \mathcal{SA}.$$

According to Kirchhoff (1984) the percentage of rescued persons with deadly injuries can be estimated with $\alpha^{\text{S4}} = 0.2$ and therefore the total number of fatalities during the time interval (T^{m-1}, T^m) due to the duration of the rescue operation equals:

$$X_2(T^m) = \sum_{i \in \mathcal{SA}} \left(X_{2,i}^{\text{killed}}(T^m) + \alpha^{\text{S4}} X_{2,i}^{\text{alive}}(T^m)\right).$$

4.2.3. Fatalities due to lack of rescue attempts

All persons who have not been rescued until the end of the SAR period T^{end} are assumed to be dead. The number of unrescued persons $X_{2,i}^{\text{unr}}(T^{\text{end}})$ can easily be calculated for each SAR area by:

$$X_{2,i}^{\text{unr}}(T^{\text{end}}) = n_i^0 - \sum_{T=T^0}^{T^{\text{end}}} \Delta n_i(T), \quad \forall i \in \mathcal{SA}.$$

Summing over all SAR areas leads to the total number of fatalities due to the lack of rescue operations:

$$X_3 = \sum_{i \in \mathcal{SA}} X_{2,i}^{\text{unr}}(T^{\text{end}}).$$

4.2.4. Fatalities due to delayed transport

After rescue the victims get only an initial treatment of their injuries. If they are not treated in an adequate manner their probability of surviving may decrease rapidly. Therefore, seriously injured have to be transported to a nearby hospital as soon as possible. Deaths due to delayed transport occur if the capacity of all reachable hospitals is exceeded. It is assumed that only injured persons of injury class S2 have to be transported to the hospital. The number of S2-injured in SAR area i who are rescued in a specific time interval (T^{m-1}, T^m) can be calculated as:

$$X_{2,i}^{\text{S2}}(T^m) = \alpha^{\text{S2}} X_{2,i}^{\text{alive}}(T^m), \quad \forall i \in \mathcal{SA},$$

where α^{S2} can be estimated by 0.4 (Kirchhoff, 1984). Including the persons with S2-injuries from the stabilizing areas and all persons who had no transport to a hospital up to time step T^{m-1} yields:

$$X_{1,i}^{\text{wait}}(T^m) = X_{1,i}^{\text{remain}}(T^{m-1}) + X_{1,i}^{\text{S2}}(T^m), \quad \forall i \in \mathcal{TA}, \quad \text{and}$$

$$X_{2,i}^{\text{wait}}(T^m) = X_{2,i}^{\text{remain}}(T^{m-1}) + X_{2,i}^{\text{S2}}(T^m), \quad \forall i \in \mathcal{SA}.$$

In time step T^m the number of available beds $B_{G_z}(T^{m-1})$ and the number of victims in injury class S2 waiting for transportation $X_{G_z}{}^{\text{wait}}(T^m)$ have to be calculated for all independent sub-graphs $G_1 = [V_1, E_1], \ldots, G_n = [V_n, E_n]$:

$$B_{G_z} = (T^{m-1}) = \sum_{\text{hosp}_z \in V_z \cap \mathcal{HP}} B_{\text{hosp}_z}(T^{m-1}), \quad \text{for} \quad z = 1, \ \ldots, n$$

$$X_{G_z}^{\text{wait}}(T^m) = \sum_{i \in V_z \cap \mathcal{TA}} X_{1,i}^{\text{wait}}(T^m) + \sum_{j \in V_z \cap \mathcal{SA}} X_{2,j}^{\text{wait}}(T^m), \quad \text{for} \quad z = 1, \ \ldots, n.$$

The number of persons $X_{G_z}^{\text{trans}}$ who will have transport to a hospital can then be calculated as:

$$X_{G_z}^{\text{trans}}(T^m) = \min(X_{G_z}^{\text{wait}}(T^m), B_{G_z}(T^{m-1})), \quad \text{for} \quad z = 1, \ \ldots, n.$$

For independent subgraphs G_z with $B_{G_z}(T^{m-1}) \geqslant X_{G_z}^{wait}(T^m)$ we assume, that

$$B_{\text{hosp}_s}^{\text{reserv}}(T^m) = \frac{X_{G_z}^{\text{trans}}(T^m)}{B_{G_z}(T^{m-1})} B_{\text{hosp}_s}^{\text{free}}(T^{m-1}), \quad \forall \text{hosp}_s \in V_z \cap \mathcal{HP}$$

additional beds of the hospital will be occupied up to its capacity. In the above formula $B_{\text{hosp}_s}^{\text{free}}(T^{m-1})$ gives the free capacity for treating additional victims in hospital hosp_s at time step T^{m-1}.

If the condition $B_{G_z}(T^{m-1}) < X_{G_z}^{\text{wait}}(T^m)$ holds in sub-graph G_z, it is assumed that the number of people being transported can be calculated as:

$$X_{1,i}^{\text{trans}}(T^m) = \frac{X_{G_z}^{\text{trans}}(T^m)}{X_{G_z}^{\text{wait}}(T^m)} X_{1,i}^{\text{wait}}(T^m), \quad \forall i \in V_z \cap \mathcal{TA}, \quad \text{and}$$

$$X_{2,i}^{\text{trans}}(T^m) = \frac{X_{G_z}^{\text{trans}}(T^m)}{X_{G_z}^{\text{wait}}(T^m)} X_{2,i}^{\text{wait}}(T^m), \quad \forall i \in V_z \cap \mathcal{SA}.$$

This leads directly to the number of injured without transport, which can be calculated as:

$$X_{1,i}^{\text{wait}} = X_{1,i}^{\text{wait}} - X_{1,i}^{\text{trans}}, \quad i \in \mathcal{TA}, \quad \text{and}$$

$$X_{2,i}^{\text{wait}} = X_{2,i}^{\text{wait}} - X_{2,i}^{\text{trans}}, \quad i \in \mathcal{SA}.$$

The number of the people $X_{4,i}(T^m)$ dying due to late transport can be calculated with the distribution function $H_i(T)$, which gives the survival rate of victims in injury class S2 after rescue. Summed over all areas we have the total number of fatalities due to late transport in time intervall (T^{m-1}, T^m):

$$X_4 = (T^m) = \sum_{i \in \mathcal{SA} \cup \mathcal{TA}} X_{4,i}(T^m).$$

4.2.5. *Fatalities due to duration of transport*

People are assumed to be saved, once they arrive at a hospital. Because the transport might take a while, it is possible that the injured die during transport as well. With the help of a shortest-path-algorithm the average travel time to the hospitals t_{G_z} for all injured in the sub-graph G_z can be estimated. Using the probability function $H_i(T)$ for the probability of surviving after being rescued, the total number of fatalities dying during transport can be calculated as:

$$X_5(T^m) = \sum_{i \in \mathcal{SA} \cup \mathcal{TA}} X_{5,i}(T^m),$$

where $X_{5,i}(T^m)$ is the number of injured from area i dying while in transit to a nearby hospital.

4.2.6. Fatalities due to lack of transport

After the end of the SAR period there may remain some injured persons without getting transport to a hospital. This occurs usually if the capacity of all hospitals is exceeded. The number of these fatalities can be calculated by:

$$X_6 = \sum_{i \in \mathcal{TA}} X_{1,i}^{\text{wait}}(T^{\text{end}}) + \sum_{j \in \mathcal{SA}} X_{2,j}^{\text{wait}}(T^{\text{end}}).$$

4.3. Resource restrictions due to local conditions

In practical emergency response it will not be possible that an infinite number of resources will work simultaneously at a single operational area. Therefore the number of resources permitted at an operational area is limited for each incidental elementary working class. The maximum value $m_{i,\text{ewc}_j}^{\max}$ is dependent on the local conditions and assumed to be known. Then the following condition has to be fulfilled:

$$m_{i,\text{ewc}_j} \leqslant m_{i,\text{ewc}_i}^{\max}, \quad \forall i \in \mathcal{OA}, \quad \forall \text{ewc}_j \in \mathcal{EWC},$$

where m_{i,ewc_j} is the number of resources working at the elementary work class ewc_j in the operational area i.

4.4. The optimization model ALLOCATE

Summarizing the above restrictions and elements of the goal function, the problem of finding an optimal resource schedule can be formalized as a dynamic combinatorial optimization model:

$$\text{Min.} \quad f(\pi) = \sum_{T=T^0}^{T^{\text{end}}} X(T) + X^{\text{end}}$$

$$\text{s.t.} \sum_{i \in \mathcal{OA}} m_i \leqslant m_r$$

$$m_{i,\text{ewc}_j} \leqslant m_{i,\text{ewc}_j}^{\max}, \quad \forall i \in \mathcal{OA}, \quad \forall \text{ewc}_j \in \mathcal{EWC}$$

with:

$$X(T) = X_1(T) + X_2(T) + X_4(T) + X_5(T), \quad \text{and}$$

$$X^{\text{end}} = X_3 + X_6.$$

The first constraint of the model ensures that only available resources can be assigned and the second constraint takes care of the restrictions described in Section 4.3.

5. Solution method

Even for moderate sizes of networks the model cannot be solved exactly; therefore, heuristics have to be used. Heuristic procedures are not guaranteed to find the global optimum, but sub-optimal solutions can be calculated in polynomial time. Among the known heuristics Simulated Annealing (SA) and Tabu Search (TS) are promising new techniques (e.g. Reeves, 1993). Although TS is a directed search procedure and does not use random components like SA does, TS does not lead necessarily to better results (Paulli, 1993). Therefore the authors implemented both solution techniques in C++.

Up to now the implementation has been tested with fictitious data. The test area consists of a city lying in a valley; there are two neighboring villages in the nearby mountains. The city is divided by a river and bridges connect the two parts of the city. Possible landslides and dam failure increase the risk of secondary disasters. To test the model different possible damage-and-loss scenarios have been assumed. For these scenarios various resource allocation problems have been generated and solved. In Fig. 6 an example of a calculated schedule is given, where the first column gives the initial resource location and the second column shows the code of the available technical resources. SA and TS were compared to hill-climbing procedures. First tests lead to the assumption that best results can be achieved by the implemented SA algorithm. To verify the overall results of the model output the computed results have been compared to expert opinion additionally. These comparisons showed that the model has a good capability to give adequate decision support for the decision makers in disaster response.

6. Conclusions

Experience with emergency management following major earthquakes shows that approximately the first 3 days after an earthquake event are essential for the performance of the relief efforts. Afterwards the probability for rescuing trapped persons alive decreases radically. With regard to the overall goal, namely reducing loss of life during this initial SAR period, three different work tasks have a high priority: SAR work, stabilizing work and immediate rehabilitation of crucial transportation

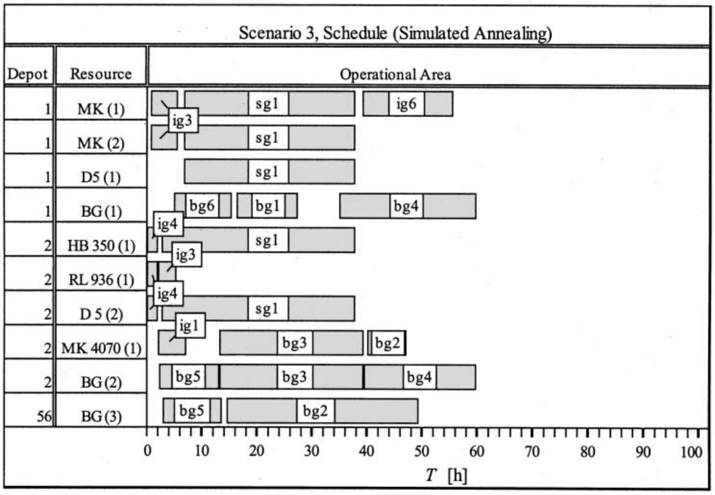

Fig. 6. Example for a calculated schedule (Simulated Annealing).

lifelines. The number of available resources to perform these work tasks is usually limited. This leads to a competition among the usable resources. To optimize the overall performance of the SAR period, the responsible decision makers have to allocate the available resources in such a way that the expected number of fatalities is minimized. Up to now this decision process has been based on the expert knowledge of the decision maker; however, due to the high complexity of the problem, the quantity of incoming information, and time pressure the problem can usually be solved only in a sub-optimal way. Computer-based decision-support systems seem to be adequate tools to improve the efficiency of the relief measures. So far the use of GIS-based systems (e.g. HAZUS; National Institute of Building Science, 1997) and other database systems (e.g. SUMA; Pan American Health Organization, 1999) in emergency management is approaching the state of the art. But these systems are usually mere information systems and do not give active decision support.

To close this gap the authors have presented a mathematical optimization model for the problem of allocating technical response resources after strong earthquakes. For this model detailed descriptions of operating areas, resources and victims were used. The problem was formalized as a dynamic combinatorial optimization problem, where the goal function minimizes the total number of fatalities during the SAR period. Because of the complexity of the model only heuristic solution procedures may be applied. Among different tested procedures, SA led to the best results. The tests and exercises have so far shown that the results are promising and that the model has a good capability to give adequate decision support for emergency managers in the training environment.

For a more practically orientated application a software package with a graphical user interface has been developed. This software may be used for exercises and it enables decision makers to verify their decision by comparing it with the output of the model.

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