Rational Resource Allocation in Mass Casualty Incidents – Adaptivity and Efficiency

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ABSTRACT

Mass casualty incidents (MCI) are highly dynamic situations in which limited available resources need to be quickly and efficiently allocated. In this paper, we suggest considerable extensions to an allocation method that we presented in earlier work. The extensions address two major challenges: First, the need to balance real-world resource usage and second, the need to adapt to changing situations. Additionally, a theoretical evaluation of the efficiency of the suggested approach is described.

Keywords

Mass casualty incidents, semantic services, agents, resource allocation.

INTRODUCTION

"3:00 a.m., motorway, a lot of cars are passing by and an unexpected accident happens. In a few minutes ambulance vehicles, fire brigades and the police are on the scene. They start working; the scene of the accident is vast (...). Some victims are already getting first medical aid and some of them are still jammed in cars. Over time new rescue assistants may arrive - or not. Only limited information about the situation is available in the beginning. (…)" - a quotation from an interview with a firefighter. This quotation illustrates that the organizations involved in mass casualty incidents (MCI), i.e., police, medical services, and fire and rescue forces, are faced with manifold challenges. The main problem for the operations manager in such situations is to manage the gap between actually available resources and necessary resources. Available resources are changing dynamically, for instance, new rescuers and transportation may arrive at the scene. All these factors make the resource allocation problem in MCI scenario very complex and different from traditional scheduling problems, *e.g,*, classical production planning, the environment is dynamically changing and information might inherently be contradictory, fuzzy, subjective. Kirn et al., 2006 discuss that agent-based approaches are preferable to classical scheduling methods for such situations. They show advantages of agent-based solutions for enterprise and healthcare scenarios. These scenarios share some characteristics with MCIs, however, the degree of dynamicity is less. Fiorucci et.al., 2004, formalized a general formulation of the real time optimal resource allocation problem as a mathematical programming problem, that is only relevant to forest fire hazard. In Fiedrich et al., 2000, resource allocation problems after earthquake disasters are solved. However, unlike our problem in this paper a schedule of resource use is constructed and they do not take into account the suitability of resources.

In this paper, we take a look at resources that are important in MCIs. Afterwards, we address one specific problem, namely the allocation of patients to ambulances and hospitals. We suggest considerable extensions of the rational resource allocation prototype presented in earlier work (Gabdulkhakova et.al.(2), 2011). These extensions deal with highly dynamic changes in the emergency scenario and investigate an optimization model that supports an even distribution of victims to the hospitals. Finally, a theoretical evaluation of the efficiency of the developed algorithm will be presented.

RESOURCES IN MCI'S

With a user-focused analysis of interaction and contents of communication for the emergency forces we could identify who is involved, what roles and tasks the forces involved in an MCI have, and what information regarding the overall situation the forces need (Gabdulkhakova et.al.(1), 2011). Based on this, we define necessary resources for the forces - resources that are needed for evacuation of victims, pre-hospital care of victims, and for information provisioning. Depending on the origin of resources functionality and capabilities can be differently structured and performed. For that reason, we decided to divide resources into two groups: human resources and technical resources (see Figure 1).

The human resources relate to the rescue workers who are participating in the handling of an accident. Here we can see that police officer, firefighter, leading medical doctor, and emergency doctor are specializations of the abstract class *Human Resource*. Based on this we can identify attributes of class *Human Resource* and its children (e.g., Name, Address, IDNumber, Qualification). Each descendant class has its own operations (e.g., for class Emergency Doctor – doing the pre-hospital care of patients(), transporting patients to a hospital(), etc.).

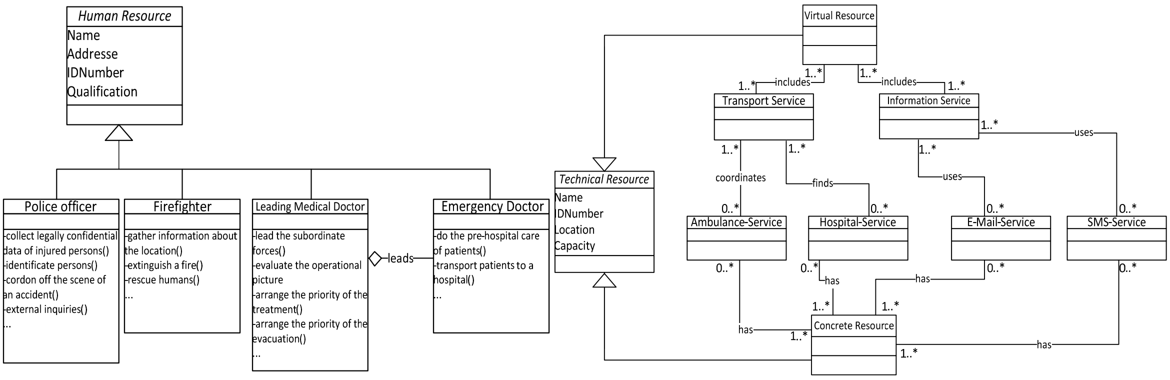

Figure 1. Representation of human and technical resources using UML-Class-Diagram

The technical resources consist of two groups – virtual resources and concrete resources, i.e., children of the abstract class *Technical Resource* . Concrete resources considered are information resources (*e.g.*, SMS-Services, E-Mail-Services) and physical resources (*e.g.*, hospitals, ambulances). Number and availability of concrete resources can be different depending on the exact situation (*e.g.*, SMS-Services have a weak signal, therefore, to inform rescue forces only E-Mail-Services will be used). The virtual resources include two types of resources - «Transport Service» and «Information Service». The virtual resources are considered to be a go between the «Transport Service» & «Information Service» and the concrete resources. In general, it is useful to connect both types with concrete resources. In particular, this connection facilitates context reasoning. In our example, by combining the class hierarchy and the relations between virtual and concrete resources with additional information, a transport service could use information about where certain ambulances or hospitals are located and whether they are free or not for the resource assignment. In order to support the execution of certain tasks the resources will be represented by modelling them as semantic services and agents (Gabdulkhakova et.al.(2), 2011). The combination of semantic services and multi-agents technologies provides a suitable basis to deal with rational resource allocation in highly dynamic situations as we will explain in further detail in the next section.

GENERAL SCHEME OF SOLUTION

In Gabdulkhakova et.al.(1), 2011, it is assumed that human and technical resources are the services that provide a specific functionality with specific characteristics. In our model, every particular resource as classified above is presented by an individual service, so that we deal directly with concrete resources and can perform the appropriate requests to them. This has the advantage that services are easy to model and maintain for providers of ambulances and hospitals. Moreover, it gives a possibility for fine-grained matching taking individual requestor requirements into account. Matchmaking will find the best suited ambulance and hospital for each individual patient. At the same time, there exist situations where several resources have similar capabilities and a number of similar tasks need to be carried out at more or less the same time. This is true, for example, when ambulances and hospitals for possibly numerous victims will have to be assigned simultaneously. Due to the "transport stop" that is typically declared by the leading medical doctor until triage has been completed, there is some time to carry out the assignment, since no vehicle will leave the scene anyhow. Here, the individually optimal solutions found by the matchmaking process, will most likely not provide an optimal or even reasonably good overall solution. Thus, we need a solution that can handle "batch" resource assignment. However, we also need an efficient way to deal with unforeseen changes in the situations: Victims may be detected after the assignment has been made or the status of a victim might become worse so that reprioritizing becomes necessary.

In the remainder of this section, we will first explain the main interactions during the resource allocation process and second take a closer look at the developed model that enables the optimization.

Model of interactions for the rational resource allocation

In order to allocate resources for operation managers in highly dynamic situations in an optimal way we use semantic services and multi-agents technologies. Figure 3 represent an UML Sequence Diagram that shows the interactions between the main components.

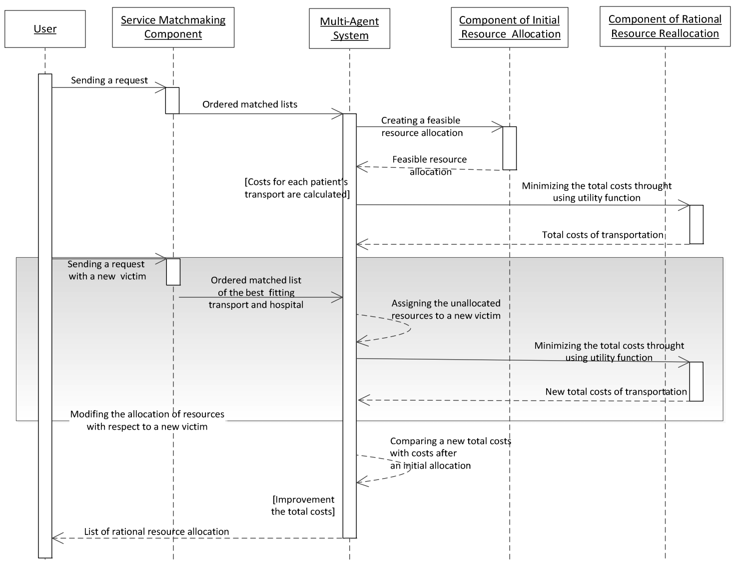

Figure 3. Main interactions by the resource allocation process

The user, *e.g.*, a leading medical doctor, sends a request to transport patients (this information needs to be provided as an input) from their current location (again provided as an input) to a destination (*e.g.*, hospitals). The requirements from the requester together with his preferences (*e.g.*, time and cost constraints) are very important for the matchmaking process by the service matching component. The result of the matchmaking will be a ranked list of more or less well matching services. Thus, each element of the matched list is a numerical characteristic, reflecting the degree of compliance of allocated resources with the "needs" of the patient (which were given in the query parameters). In the component of initial resource allocation a feasible allocation will be created. On some occasions you may find that the same vehicle might be the best solution for several patients. However, a vehicle can be used to transport one patient only. The same problem arises for hospitals that have a limited number of operation rooms or free beds. We solve such kind of problems through mutual concessions: using minimum loss of the patient in the appropriate characteristic (degree of compliance) of the selected resources as the criterion. After that, the costs for each patient's transport are calculated. The second component is responsible for rational resource reallocation. Agents "Patient" negotiate with each other about possible resource exchange. They use the developed optimization model and criteria function to minimize the total costs of victims' transportation to hospitals. Based on these calculations and in case of improvement of the total costs, a new list of resource allocation will be produced and send, *e.g.*, to a leading medical doctor. The proposed system has been implemented and evaluated. The analyses of results showed a significant reduction of the total cost(Gabdulkhakova et.al.(2), 2011).

In our prior work, we did not address dynamically changing situations. Figure 3 also shows the extension of the original algorithm that we propose for a new request for a new victim's allocation in the highlighted part of the diagram. The solution is based on the result of the service matching component - a list of best fitting transport and hospital resources. Instead of using the component of initial resource allocation, an agent of a new victim needs to discover the unallocated resources in his ordered matched list (*e.g.*, another victim has been already allocated to these resources during the first request). After that the component of rational resource allocation starts to work. As we already have our rational solution of resource allocation for the first request, the agent of a new victim needs only to initiate with other agents "Patient" in order to improve the achieved result.

Optimization model of the rational resource allocation in MCI

Any activity, including the allocation of resources in emergency situations, may be evaluated in terms of the criterion of rationality. In our case, agents that solve the problem have a goal that is achieved by rational behavior. For this purpose, we have developed an optimization model of the rational resource allocation in MCI (Gabdulkhakova et.al.(2), 2011). The objective function reflects the cost of transporting victims to hospitals and takes into account the preferences of assigned resources. However, it does not yet adapt regarding the even distribution of victims to hospitals. We could change that by either adding new constraints or by modifying the objective function, Since even distribution of patients is a soft constraint, only, we have decided for the latter. We develop a function U that reflects the increased costs of admission of patients owing to a greater flow than the hospital can service under normal conditions: $\prod_{k=1}^{R} U_k(\sum_{i=1}^{N}\sum_{j=1}^{M} X_{ijk}) \to \min$

where $U_k(q) \geq 1$; U_k^{max}- the optimal number of patients that the hospital k can take up at a time; if $q \leq U_k^{max}$ then $U_k(q) = 1$; if $q > U_k^{max}$ then $U_k(q) > 1$ and the larger q the more the cost of admission of patients , $\sum_{i=1}^{N}\sum_{j=1}^{M} X_{ijk}$ - the total number of patients transported to hospital k.

Thus, an adapted version of the optimization model with a proposed even distribution function of victims to hospitals is the following:

$$F = \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{R} \frac{X_{ijk}[Z(P_i, A_j)D(P_i, H_k)]}{S_{ij} * S_{ik}} * \prod_{k=1}^{R} U_k(\sum_{i=1}^{N}\sum_{j=1}^{M} X_{ijk}) \to \min$$

where $P=\{P_1,\ldots,P_N\}$ – set of patients; $A=\{A_1,\ldots,A_M\}$ – set of vehicles; $H=\{H_1,\ldots,H_R\}$ – set of hospitals; i – index of a patient; j – index of a vehicle; k – index of a hospital; X_{ijk} – the fact of delivery of patient i by the vehicle j to the hospital k (X_{ijk}=1, if patient i is transported by the vehicle j to the hospital k, or X_{ijk}=0, otherwise); $Z(P_i, A_j)$ – the cost of transporting the patient P_i by a vehicle A_j; $D(P_i, H_k)$ – the distance from the location of the patient P_i to the hospital H_k; S_{ij} – coefficient reflecting suitability of assigned resource vehicle j for transporting patient i, $0 \leq S_{ij} \leq 1$; S_{ik} – coefficient reflecting suitability of assigned resource for transporting patient i to hospital k, $0 \leq S_{ik} \leq 1$.

The resulting mathematical model is more flexible than previously described Gabdulkhakova et.al.(2), 2011. Introducing the function U takes into account the specific features of the problem associated with the ability to service victims. Its application allows us to avoid decisions that are good in terms of material costs, but totally unacceptable from the standpoint of common sense.

EVALUATION OF THE RESOURCE ALLOCATION ALGORITHM'S EFFICIENCY

To evaluate the efficiency, it is necessary to estimate the number of communications of agents, since the algorithm is based on the communications of agents. We consider that time is proportional to the number of communications. This is reasonable since no resource consuming computations are necessary and no huge data volume is expected. Thus neither computation time nor memory consumption influence efficiency. There are two stages in the algorithm:

The first stage. Let it be N – number of patients, M – number of resources, and the number of resources is more than the number of patients. To calculate the maximum number of possible communications we use three types of agents: patients, transport, and hospitals. To identify the agents "Transport" and "Hospital" we will use agent "Resource". In the worst case, all victims will be assigned the same resources. Then the agent "Resource" has to send N messages in order to determine what would be the loss of each victim in the assignment of the resource. After this, the agents "Patient" send replies to the agent "Resource". The number of messages will be 2*N. Further, the number of victims who need to allocate a resource is decreased by one. The procedure is repeated, and the number of messages will be 2*(N-1). The procedure stops when only one victim remains. Thus, we obtain the following formula for maximum number of communications: $2\sum_{i=0}^{N-1}(N-i)$

It appears that the worst-case time does not depend on the number of available resources. Quite obviously, however, we expect lesser messages if more resources are available since it then are less likely that the same resources are assigned multiple times.

The second stage. Each agent "Patient" looks through all resources, except those already appointed, and asks them for occupation. If the resource is occupied by no one, it means that we already have a good solution. Inoccupation of resource means that there is another resource that is more suitable. According to the problem the number of resources is more than number of patients (i.e., M> N). Therefore, only N resources will be occupied. Thus, we have (N-1) - the maximum amount of resources which agents "Patient" can exchange. We have N agents "Patient". Each of them sends (N-1) requests to other agents to exchange resources and receives in return for an exchange option. Thus, we have 4 * (N-1) messages for each agent Patient, or 4 * (N-1) * N - total number of messages. Now to the group of victims who have already rationally allocated resources, a new victim - "PatientNew" – is added. At first stage a maximum of communications for agent "PatientNew" in order to find a free resource will be (N +1). At the 2nd stage the agent "PatientNew" need to communicate with each of the N agents "Patient" for resource reallocation similar to the above scheme. The resulting difference in communication at the 2nd stage is as follows: if the agent involved in the general reallocation of resources from the very beginning, the number of communications would be to (4 (N +1-1) (N +1) -4 (N-1) N) = 8N more than without it. In the case where the agent is involved in the reallocation of already formed plan, the number of communications obtained 4N. According to these calculations the complexity of our algorithm is polynomial $O(n^2)$.

Due to theoretical calculations the number of communications is approximately cut in half. Thus, we conclude that when a new victim arrives there is no need to fully replan. More efficient in this case is the use of the proposed scheme of solution: no need to wait until the current calculations are finished. Agent based methodology allows to engage in the process of constructing a plan of resource allocation at any time until the system is in the calculations. Thus, even if the patients arrive faster than the calculations are performed, the algorithm will do its job.

CONCLUSION

In this paper, we have introduced an optimization model taking into account specific features of the problem. A suggested criteria function makes possible more flexible resource allocation in dynamically changing environment. The theoretical evaluation of the resource allocation algorithm was demonstrated. In our ongoing work we are extending our implementation to deal with time calculations concerning re-planning rates. This work is developed in the SpeedUp-Project[1] in close cooperation with our partners from different rescue organizations and will be evaluated in real-life MCI situations.

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[1] SpeedUp is funded within the Federal Government's program Research for Civil Security (call Rescue and protection of people) by the Federal Ministry of Education and Research. (http://www.speedup.uni-jena.de)