A TWO-STAGE APPROACH FOR THE EMERGENCY SERVICES COORDINATION PROBLEM IN A ROAD ACCIDENT

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ABSTRACT

The coordination of emergency services in road accidents is essential to ensure a quick intervention in critical situations. The number and kind of resources assigned must be determined dynamically, as not all the accident variables are known when an alert is received. Moreover, vehicles and intervention units have to be assigned after the accident takes place. Thus, the decision making process has to be done within the intervention time window and response time becomes critical. This paper describes the major characteristics of a cluster first-route second optimization algorithm suggested to tackle the emergency services coordination problem in order to reduce their response time in critical situations. This algorithm combines heuristic methods and Constraint Satisfaction Problem techniques in a two-stage procedure: a first phase where the real geographic data is rearranged to ensure the time constraints fulfillment and a second one, which consists on available resources' allocation and optimal routes assignment.

INTRODUCTION

The complexity of tasks carried out in a road accident requires the intervention of multidisciplinary rescue services, i.e. Police Service, Medical Service and Fire Service, and their coordination is a key issue to ensure an effective intervention. Therefore, correct management of these three heterogeneous fleets is necessary to distribute units and respond to dynamically changing real needs.

Such a coordination is highly complex, since not all the information relative to accident variables is known from the very beginning and the available information usually contains uncertainty. Furthermore, although some collaboration protocols are defined, they only regulate services interaction at the accident scene, but they not include general norms about resources' assignation (Samur, 2006). Centralized communication, coordination and decision tasks would improve rescue services response, reducing rescue time and optimizing the available resources.

Attending an accident basically consists of deciding which resources are assigned and from which depot they have to be selected, taking into account all the accessible information and that the objective is to reduce the route travel time. The allocation task is performed using the fleet variables, including available units type and state, but not considering vehicles crew assignment.

Time restrictions are naturally imposed due to the reaction time is primordial to save possible accident victims. Thus, the routes planning expended time becomes critical, since they have to be assigned within intervention's time window. Road network configuration and depots (fleet bases) distribution are also important issues that determine the emergency fleets' capability to respond a concrete situation.

The number and kind of mobilized resources in a particular situation depends on the accident variables, such as the number of involved vehicles, traffic ratio on the road and time when the accident takes place or whether there are injured victims or not. Furthermore, resources are dynamically assigned since information flow is continuous from the moment the accident occurs until services finish their action.

A simulation platform (Ramos et al., 2006) has been designed as a distributed application based on CORBA (OMG, 2004) to simplify the coordination and communications between modules. A *Geographical Information System (GIS)* module manages all the static and dynamic geographical data in the system, such as depots location and the road network configuration (Ramos et al., 2005), used to compute realistic travel time and costs. However, the huge amount of data provided by these databases would make the problem, which falls into the Vehicle Routing Problem (VRP) category (Bektas, 2006), intractable in a real-world case due to the computation time.

Due to the NP-Hardness of the problem, no exact algorithm can be assured to find optimal solutions within reasonable computing time, so near all the solution techniques for this problem are heuristics (Laporte et al., 2000) and metaheuristics (Glover and Kochenberger, 2003). These methods has demonstrated being effective in the search of good solutions within acceptable calculation time, though solution's global optimality may not be guaranteed in many cases.

This paper presents a cluster first-route second (Dondo and Cerdá, 2007) two-stage approach to tackle the emergency services coordination problem. In the first phase, introduced in the next section, the GIS data is pre-processed and clustered in order to reduce the significant computing burden when shortest paths have to be calculated in order to find optimal routes, while keeping exact information about travel time. The following section describes the second phase, where the different units are allocated and the geographical information provided at the first phase is used to determine the optimal routes. Finally, some approach's limitations are outlined in the last section.

CLUSTERING PRE-PROCESS

Clustering geographic data has demonstrated to be an effective strategy to tackle routing problems in logistics (Dondo and Cerdá, 2007), transportation (Anily et al., 1999) and network communications (Frey and Görgen, 2005) when all the information about visit points is known. Nonetheless, in the case of road accidents in a realistic scenario the information remains unknown during the clustering process, becoming available when the accident takes place. So, a different clustering strategy should be adopted in order to reduce the computation time at the solution stage.

The emergency service management may be seen as a multi-depot VRP with heterogeneous fleet (Guimarans et al., 2006). The goal of the geographic data rearrangement is to reduce such a multi-depot VRP approach to a set of single-depot VRP problems, where only one for each emergency service has to be solved when an accident occurs. Therefore, variables' domains are reduced, improving the response time of the optimal solution search algorithm.

With this objective, GIS information is preprocessed by classifying the GIS nodes according to distance and traveling time from the different depots. Thus, each node is only reachable by a vehicle whose base is located at the depot which minimizes distance and traveling time, creating a cluster-based structure. At this phase, a common heuristic A* procedure (Russell and Norvig, 2003) is used to classify the geographic information into separated clusters.

A* procedure is optimally efficient, i.e. no other search algorithm guarantees the expansion of less nodes than A* with an appropriate heuristic function. The algorithm evaluates nodes during the search combining the accumulated cost for reaching the node and the estimated distance from the node to the goal. Thus, A* uses a cost estimation of the better solution through the evaluated node to decide the search direction. Since clustering stage's objective is to minimize distance and traveling time, the better strategy consists on expand nodes with minimal evaluation function value.

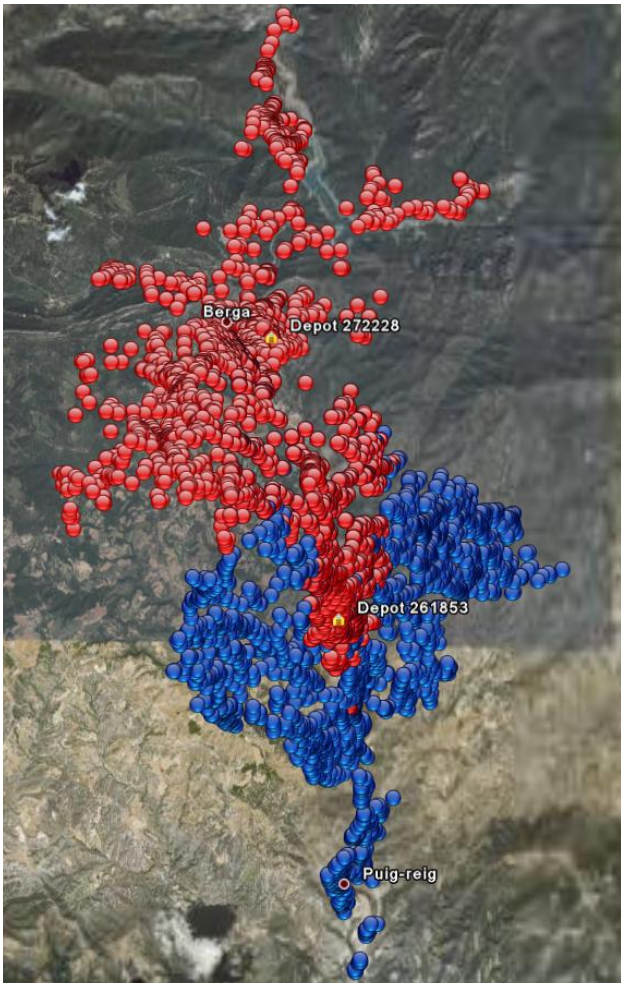

Figure 1: Example of clusters generated during pre-processing stage for two different emergency services in a rural area.

In the case of emergency services problem, where a goal node associated to an accident is not defined in the pre-processing stage, traveling distance and time estimations from a concrete depot to an accident may not be done. Therefore, every single node should be considered as a potential accident node, so no particular direction may be pondered during the search in the clustering process. For this reason, an uniform null cost heuristic function is introduced in the clustering algorithm. According to this strategy, each path is explored using only the traveling accumulated cost until the time service restrictions are not fulfilled, delimiting thus the cluster edge, as shown in Figure 1.

The uniform null cost heuristic never overestimates the real cost of getting from one node to another, being so an admissible heuristic. In addition, the uniform null cost heuristic function is consistent, since evaluation function's value monotonically increases during the search. These properties guarantee the optimality of all paths included in a cluster and ensure that no optimal solution may be discarded during the search (Russell and Norvig, 2003).

As the algorithm always explores nodes with minimum associated cost at each iteration, it is possible to assure that the corresponding determined path from the depot to any node in the cluster is minimum. Since any suboptimal path to a particular node has a larger cost than the optimal one, it can be demonstrated that the suboptimal path will never be explored and the optimal solution will be returned. Thus, a shortest path determination task is performed during the process and nodes are reordered into the cluster structure. So, when an accident notification is received, a shortest path approach from the depot to the accident scene is known, achieving an important calculation reduction.

The clustering pre-process stage provides a set of separated cluster structures, where geographic data is rearranged according to shortest path graphs. Thus, solution's computation time is reduced since it should be calculated over a reduced graph instead of a complete one. These graphs follow a radial configuration, since they contain information about traveling distance and time from the corresponding cluster's depot to all possible geographical nodes included within the cluster. This characteristic allows to simplify routes planning from the selected depot to the accident scene, reducing thus the wasted calculation time within the intervention's time window. On the other hand, such a configuration does not include neither data concerning point to point movements inside clusters nor information about returning routes from the accident scene to the corresponding depot. However, this kind of routes scheduling may be done once resources are allocated and a first response to accident needs has been given within the intervention's critical time window. In this case, a different heuristic function should be used to take into account route's characteristics, as well as an appropriate planning to respond service's protocols.

EMERGENCY SERVICES ALLOCATION

Routes Planning

The fact that Medical and Fire Services must return to their origin depots before attending another accident simplifies the routing problem, so two-nodes or at most three-nodes routes should be calculated, as shown in Figure 2. On the other side, Police Service can perform different actions in several accidents before returning to their origin depot, although a new destination cannot been assigned until their service at the accident scene has ended. In this special case, a police vehicle returning to its base can be interpreted as a new depot with a single vehicle in order to reallocate services on runtime simulation.

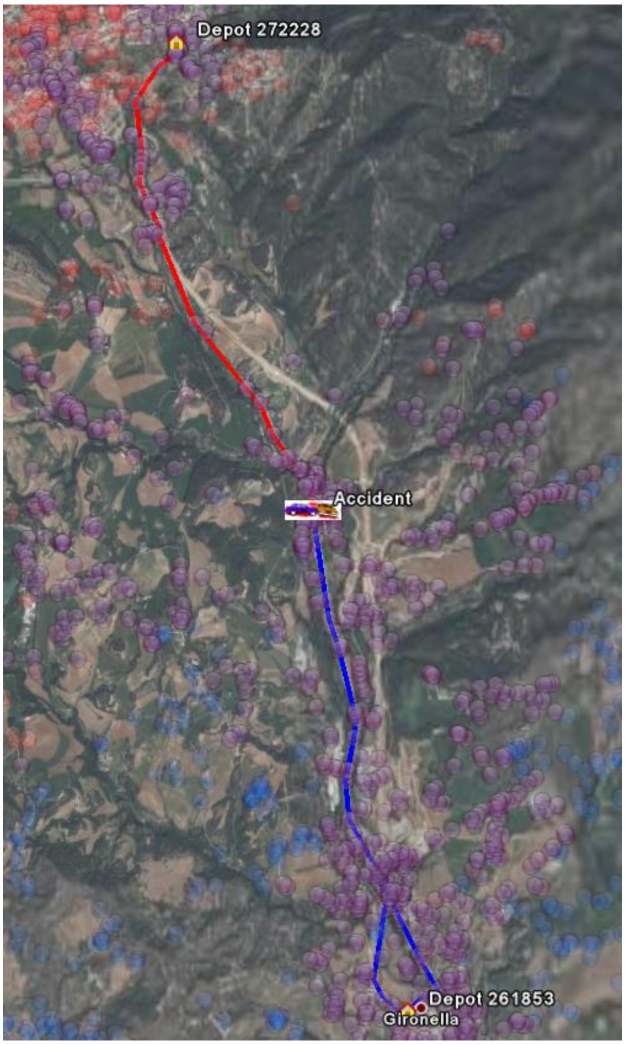

Figure 2: Example of calculated routes within two clusters located in a rural area. Nodes belonging to clusters are shaded.

The clustering process made in the first stage provides information about optimal routes between depots and all nodes included within the corresponding cluster. Therefore, all nodes classified in a particular cluster may be easily located and the minimal route may be obtained directly from the corresponding shortest path graph. Clusters' construction assure that these paths will minimize traveling time, so the optimal route to an accident may be known from the moment it takes place. Moreover, this geographic data classification provides a mechanism to assign depots from which resources are allocated, since nodes are associated to clusters corresponding to those depots which minimize travel time between the two points. In many cases, specially in urban areas with a dense road network configuration, same nodes are included in separated clusters. Thus, an accident occurred within these areas may be reachable from different depots while keeping fulfilled intervention's time restrictions. Then, a depots list ordered according to travel time will be returned, providing several options to respond to a particular accident aiming to better fit all imposed restrictions. Simulation results confirms the efficiency of the applied strategy, achieving a 95% computation time reduction with regard to the solution obtained with a commercial package, while keeping guaranteed route's optimality. Moreover, average computation time per route remains lower than 0.5 seconds, providing a short response time within the critical time window.

In some cases (e.g. accident occurred in an isolated area, traffic jam, etc.), a solution fulfilling the imposed time constraints may not be reached. Thus, these constraints may be avoided and minimizing the response time becomes the objective of the relaxed optimization routing problem. For this purpose, several routes should be calculated in order to provide a list of different options to respond to accident's needs. First, geographically nearest depots to the accident node are determined to obtain a set of candidate clusters. Then, nodes belonging to each selected cluster edge are filtered to choose those whose distance to the accident scene is lower, aiming to reduce the number of routes that should be evaluated. Applying an A* procedure with an appropriate heuristic function, routes are determined while keeping guaranteed their optimality and a reasonable computing efficiency. Using the geographic distance between the evaluated node and the accident point as an heuristic function, admissibility and consistency criterions are fulfilled, so routes returned by the algorithm will be minimal. Furthermore, they are obtained expanding only the essential nodes. As a result, a list of optimal routes ordered by travel time from several depots will be obtained, as in the previous case. Simulation tests have provided an average computation time reduction per route near to 55%, regarding to the commercial package performance.

Once vehicles belonging to different services are assigned to a particular accident, several routes should be calculated. Medical Service should determine whether hospitalization is required or not and to which hospital victims have to be transported. On the other hand, all resources except Police Service units should return to their respective depots before attending another accident. Therefore, different point to point routes have to be calculated during the intervention. As the origin and ending nodes are known, A* algorithm may be applied using the geographic distance as an heuristic function. Notwithstanding, since hospitals' location is known in the clustering stage, returning routes to depots may be calculated in this phase. Thus, these routes would be assigned automatically, achieving a computation reduction in the solution stage. Nevertheless, runtime routes determination permits taking into account several factors, such as traffic situation or service perturbations. However, pre-processing strategy provides a static route that may be used as an heuristic function for runtime routes calculation more accurate than geographic distance.

Police Service units can perform different interventions in several accidents before returning to their depot. Therefore, a Police resource located close to an accident node when it takes place may be assigned in order to reduce the response time. In the case of an accident node that belongs to a cluster, routes from different Police units located within the cluster edge to the accident node should be calculated and compared to those which come from the depot. Again, an A* procedure with an heuristic function that consists on the geographic distance between two points is used to determine units' routes. So, resources capable of minimizing the travel time will be assigned although they were not in the depot at the moment the accident occurs. On the other side, when an accident takes place in a node not classified into any cluster, Police units located within nearest clusters may be used to calculate different possible routes using the same A* strategy. Thus, these resources will add several route options to the paths set determined for each depot, being assigned the one that minimizes the response time.

Constraints Model

The problem can be interpreted as a Vehicle Routing Problem (Bektas, 2006) with some additional constraints. First hand, a multi-depot consideration should be tackled since every rescue service owns different bases scattered along the territory. Moreover, several kinds of vehicles are located at each depot, constituting an heterogeneous fleet. Problem's characteristics also impose tightly restricted time windows, since a quick actuation is required on a road accident. Traffic ratio on the road, seriously injured victims or the number of vehicles involved in the accident are some of the variables that determine the tightness of the time window restriction applied to a specific accident.

The objective is to assign resources to accidents according to the implicit restrictions of the problem, which falls into the Constraints Satisfaction Problem (CSP) category. System constraints are related to the available resources and specially to time windows. For this purpose, CSP techniques (Marriott and Stuckey, 1998) are used to find a feasible solution. In order to solve this problem a commercial solver based on constraint satisfaction technology is used.

Two elements are combined in the constraint satisfaction problem: the model where the decision variables, the problem constraints and the objective function are defined; the solution search algorithm which selects a value in the domain of each constrained variable, so that all the constraints are satisfied.

The objective function of such a constrained problem is to minimize the travel time from the depot to the accident scene. In this case, reducing economic and distance costs or units used to respond to a particular accident is not imposed, since resources may only attend one single accident before returning to their origin depot. The number and kind of resources send to an accident depends on the number of seriously injured victims, how many vehicles are involved and whether there is fire or not.

The main constraint reflects the maximum fixed response time, a relevant factor that influences on injuries seriousness. Usually, medical units should arrive to the accident scene within first ten minutes after the accident occurs (Al-Ghamdi, 2002). For this reason, clusters are generated in the pre-processing stage according to this time restriction, so a response time fulfilling the proposed pattern can be assured if the accident takes place within cluster's edge. Moreover, optimal shortest path from the depot to the crash scene will be known. Notwithstanding, if an accident takes place in an isolated area time restrictions may not be fulfilled. Therefore, maximum response time constraint may be avoided and the arising relaxed problem is solved aiming for minimizing the travel time.

On the other hand, all resources of a particular depot may not be assigned to a single accident. Therefore, no cluster's area may rest uncovered in order to respond to several accidents taking place in a brief period of time. In the case of Medical Service and Fire Service, this constraint also implies that their depots may not rest with no vehicles. The reason is that medical and fire units may not be assigned to another accident before returning to their origin depot to perform maintenance and replacement actions, so response time could be critically increased even though in accidents occurred within the cluster. On the other side, this constraint is not applied for the Police Service units, as they can perform several interventions in different accidents without returning to their depot.

Another constraints are imposed according to the VRP formulation (Dondo and Cerdá, 2007). For example, each vehicle is assigned to a single depot, to which it should return after an intervention. Furthermore, each accident should be served at least by one police unit. Necessary medical and fire units and additional police resources will be assigned taking into account accident's variables.

The information obtained at clustering stage is used to reduce the solution search space. Moreover, an accident may be associated to a particular depot with a minimal computational cost, since either the accident location belongs to a specific cluster or the distance from the accident node to close clusters' edge may be easily calculated. Thus, the solution search is simplified to explore only nearby clusters, reducing the search space while keeping guaranteed path's optimality.

The solution search algorithm selects a value in the reduced domain of each constrained variable and checks that all the constraints are satisfied. Restrictions fulfillment implies that resources located at the selected depots may respond efficiently to an accident minimizing the response time. Nonetheless, in some cases such an optimal solution may not be reached, since vehicles can be assigned to different accidents and particular crash variables may not be satisfied by the available fleet in a selected depot. Then, selecting a different depot provides a suboptimal solution that permits constraints accomplishment except the response time restriction. Thus, this strategy gives an optimal or suboptimal solution while achieving an important computational cost reduction.

METHODOLOGY'S LIMITATIONS

The information flow is continuous from the moment the accident occurs until services finish their action. In addition, the information may arrive from different sources, containing a large uncertainty. Therefore, the available information during solution stage is dynamically changing, since not all accident variables are known until the first unit arrives to the accident scene. So, the solver is forced to check resources' availability and problem's time constraints in a continuous process during the intervention. For this reason, different resources may be reallocated several times for a particular accident according to the known needs.

On the other hand, roads state may change from the moment the accident takes place to service end, so shortest paths calculated at clustering stage may become non optimal. Platform's modularity allows to introduce different traffic modeling approaches, such as continuous traffic flow (Gazis, 2002) or multi-agent based systems (Dia, 2002), to simulate a realistic scenario. In a real situation, vehicles' GPS information could be used to determine traffic state, since their geographical position and movements are well-known. Thus, the corresponding route to the accident scene should be recalculated and, in some cases, resources may be reallocated. So, clusters can not be defined as rigid structures, but nodes included in foreign clusters may be reachable by vehicles belonging to a particular depot in order to find a feasible solution taking into account traffic situation.

Notwithstanding, cluster's shortest paths information may be used as an heuristic approach to calculate new routes, reducing search's complexity. Thus, paths included within a particular cluster may be determined according to nominal results obtained at the clustering process and the instantaneous roads state.

CONCLUSIONS

The suggested two-stage approach provides an effective strategy to tackle the emergency services coordination problem, seen as a multi-depot VRP with an heterogeneous fleet and tight time windows.

In the clustering pre-process stage, the search space is reduced transforming a multi-depot approach into a set of single-depot problems. Moreover, this task determines a radial shortest path graph that ensures the optimality of any route calculated within a cluster's edge from a depot to the accident scene. In a second stage, individual single-depot problems are solved using CSP techniques and the information obtained at the clustering process. This approach allows to reduce computational burden and, in consequence, wasted time in the decision making phase, since an accident may be assigned directly to a particular depot.

On the other hand, the geographical data rearrangement done during the pre-processing stage provides an accurate heuristic approach that may be used in the solution phase for routes planning. This heuristic is specially relevant in those cases where time window constraints are not fulfilled.

Nonetheless, the proposed strategy has some limitations, since clusters are calculated at a pre-processing stage with nominal values for travel time between nodes and accident variables are dynamically changing during resources assignation. These limitations may be smoothed considering traffic perturbations in simulation runtime and using clusters data as an heuristic function for routes calculation, as well as permitting resources reallocation in the solution phase.

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