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A multi-agent approach for integrated emergency vehicle dispatching and covering problem

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ABSTRACT

The most important decisions that should be made by emergency vehicle managers are related to the allocation and the covering problems. The allocation (or dispatching) problem consists of deciding which vehicle must be assigned to assist an emergency in the best times. The covering problem aims at keeping the region under surveillance well-covered by relocating available vehicles. As components are geographically distributed, decentralized solution approaches may present several advantages. This paper develops a decentralized distributed solution approach based on multi-agent systems (MAS) to manage the emergency vehicles. The proposed system integrates the dispatching of vehicles to calls with zone coverage issues. This integration means that allocation and covering decisions are considered jointly. The idea of MAS has been applied in many others real-world contexts, and has been proven to provide more flexibility, reliability, adaptability and reconfigurability. To our knowledge, there is no existing work that uses MAS for real-time emergency vehicle allocation problem while accounting for the coverage requirements for future demands. We propose a multi-agent architecture that fit the real emergency systems, and that aims at keeping good performance compared to the centralized solution. The objective is to coordinate agents to reach good quality solutions in a distributed way. For this purpose two approaches are examined. The first one is used to show the impact of distributing data and control on the solution quality, since the dispatching decisions are based only on local evaluations of the fitness. The second approach is based on implicit agents' coordination using a more refined and efficient auction mechanism. The performance of each approach is compared to the centralized solution obtained by solving the proposed model with ILOG CPLEX solver. The obtained results show the importance of the coordination method to keep a good quality of service while distributing data and decision making, and prove the performance of the second approach.

1. Introduction

Emergency vehicle fleet management plays an important role in the improvement of the quality of services offered by public organizations like rescue personnel, paramedics, fire protection and police. In real world operation of emergency organizations, when an emergency occurs, a call is received by a specialized emergency center, and the first step is to determine information related to the call like its severity degree and its location; then deciders determine which vehicle must be sent to assist the call. In this context, the two most important decisions that should be made by emergency vehicle managers are related to the allocation and the covering problems. The allocation problem consists of deciding which vehicle must be assigned to an emergency, in best times. The covering problem aims at keeping the region under surveillance well-covered by relocating available vehicles.

In a recent paper (Ibri et al., 2009), we have developed an optimization model that considers allocation and covering decisions jointly. It deals not only with the real time vehicle allocation problem, but it also takes into account simultaneously the coverage concerns for future demands by relocating and diverting the on-route vehicles and remaining vehicles among stations. Such a model is said to be *integrated*, and it is motivated by the fact that the allocation and covering decisions are tightly related: as the number of vehicles is limited, dispatching a vehicle to a call makes zones less covered, and thus reduces the possibility of answering properly future calls. It is then intuitively expected that integrating allocation and covering decisions in the same model should improve the system performance on the long range. The value of this integration has been investigated in Ibri et al. (2010) by comparing the integrated model with the

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non-integrated one. The latter consists in consecutively solving the allocation problem and the covering problem. The allocation decisions are found first, and then used to solve the covering problem. For this comparison, the solution approach was based on a heuristic algorithm combining ant colony optimization and tabu search.

While the method used in Ibri et al. (to appear) is a *centralized* approach, the solution approach developed in the present paper is rather a *decentralized* one. In fact, the issue we are investigating is naturally distributed, since it deals with components that are geographically distributed. When solving the corresponding problem in a centralized way, we assume that a central decision maker knows at each instant the locations, the states, and the destinations of all the vehicles for all the zones in the system. While modern technologies can provide this kind of information, a decentralized solution approach can be sometimes desirable in the context of emergency vehicle fleet management. In fact, such a distributed solution may present the following general advantages (Wooldridge, 2002):

- They respect the distributed nature of the problem and could make its understanding and implementation easier.
- They are more adaptable because the different components of the system have to make less complex decisions. They are in fact able to better control their local environment (vehicles, crews, etc.), and react to changes faster. In contrast, centralized optimization algorithms can be sensitive to information updates: a minor modification in information may have impact on the schedules of many vehicles.
- Information integrity for each component of the system may easily be achieved.
- The system is decomposed on independent processing units. This can increase the computing power considerably, and so the problem solving may be accelerated. In contrast, the time required for the centralized optimization algorithm may not permit timely response to the emergency events when we deal with a large number of vehicles and calls, especially when the supervised region is large and the frequency of arriving calls is high (in case of disasters for example).
- Another important matter generally inherent to the centralized architecture is that the failure of the central decision maker will lead to the failure of the whole system, which may have serious consequences in the context of emergencies.

As a distributed solution, multi-agent systems (MAS) have been proposed within the computer science literature. Such systems are composed of multiple interacting intelligent software units (i.e., agents) that are linked to physical or functional entities (e.g., vehicles, calls). Agents are able to act autonomously by pursuing their own interest. Even if each independent agent has only a partial local view of the system, agents may interact with each other, for example using information exchange and negotiation mechanisms. The MAS approach seems to be a promising solution for controlling distributed systems, providing more flexibility, reliability, adaptability and reconfigurability. A key issue is how to configure agents such that their behavior yields a near-optimal solution for the system as a whole. In fact, coordination and information exchange between agents are among the central parts that have to be considered to give the distributed approaches strength, in order to reach good performance for the system.

The idea of MAS is elegant and it has been applied in many real-world contexts, such as computer games, defense systems, mobile technologies, transportation, logistics, etc. However, literature on the application of MAS to deal with emergency vehicle dispatching and covering issues is scarce. In this paper, we develop a multi-agent system to solve the emergency vehicle allocation and covering problem. Then, we investigate how much distributing decision making affects the system performance, by comparing the proposed MAS with the centralized solution. Finally, we propose and test a coordination mechanism that improves the solution in the distributed context.

The remainder of the paper is organized as follows. In the next section, we give an overview of related literature. In Section 3, we present the centralized optimization model. In Section 4, we develop the multi-agent-based solution concept, and we discuss the agents' interactions and coordination. Experimental results on the proposed multi-agent solution approaches are given in Sections 5 and 6 concludes the paper.

2. Literature review

There are two important classes of studies in relation to the research presented in this paper. The first class concerns the centralized models and solutions for the allocation and covering problems, whereas the second one is related to the use of multi-agent systems for decentralized decision making.

2.1. Models and solutions for the allocation and covering problems

The allocation problem was formulated in Haghani et al. (2003) as a model that minimizes the total travel time in the system. Some simple strategies like the nearest vehicle or the vehicle which was idle for the longest time can also be applied to choose the responder vehicle. In Andersson and Varbrand (2007), the decision on the vehicle to dispatch is made according to the priority of the call: for the highest priority call, the vehicle with the shortest travel time is dispatched, otherwise the vehicle that affect the least the covering issue is chosen. To avoid making calls with less priority waiting for long time, the authors use pseudo priorities that are incremented when a call is not served in some time limit.

To keep good coverage of the supervised region, three types of covering models have been proposed in the literature: static models, probabilistic models, and dynamic models. The most important static models are: the *Location Set Covering Model* (LSCM) proposed by Toregas et al. (1971) that consists in minimizing the number of vehicles to cover all demand points; and the *Maximal Covering Location Problem* (MCLP) proposed by Church and ReVelle (1974) with the aim to maximize population coverage subject to limited vehicle availability. Other static models maximize coverage with several types of vehicles at the same time (Schilling et al., 1979). In Daskin and Stern (1981), the authors extend the LSCM to the multiple coverage of demand' nodes. In Hogan and ReVelle (1986), the authors maximize the number of points covered more than once using hierarchical objectives. In Gendreau et al. (1997), two coverage standards $r_1 < r_2$ are used, all the demand points must be covered within r_2 time units and a proportion α of population must be covered within r_1 time units. The static models ignores that when vehicles are dispatched to calls, some points are no longer covered. In probabilistic models randomness is introduced in the availability of vehicles, the service time or the traveling time. For example, in the maximum expected covering location problem (Daskin, 1983), it is assumed that each ambulance has the same probability q of being unavailable to answer a call. Other queuing models have been proposed in the literature to analyze the performance of emergency services at different situations: see for example Chaiken and Larson (1972). In dynamic models, relocation decisions are periodically made. In Kolesar and Walker (1974), a relocation system was proposed for fire