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BACHELOR THESIS

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Emergency services shift plan optimization

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1. Introduction

1.1 Problem definition

One of the primary challenges faced by emergency medical service providers (EMS) revolves around determining the optimal availability schedule for their ambulances at specific depots. The primary objective is to maximize the number of successfully handled incidents while minimizing the operational costs associated with the ambulances. This allocation of ambulances and their availability is commonly referred to as a shift plan.

A shift plan entails assigning shifts and ambulances for a given time interval, typically a single day. It serves as a representation of when ambulances are available throughout the day.

Each shift represents a time interval during which an ambulance crew operates the vehicle, rendering it available for emergency response. Ambulance crews may possess specialized skills or equipment, such as the inclusion of a doctor or experienced personnel. Similarly, different ambulances can vary in size or possess advanced medical tools. To capture these distinctions, each ambulance is assigned a specific type.

Ambulance types provide an abstraction of these varying scenarios and specify the incidents they are equipped to handle. For instance, certain incidents may require specific tools or a larger ambulance. Consequently, only select ambulances may be suitable for handling such incidents. Ultimately, our primary concern int this regard is determining whether a given ambulance can effectively respond to a particular incident, based on the mapping between ambulance types and incident types. Hence such abstraction is sufficient for our purposes.

Throughout the day, only one shift can be assigned to each ambulance, and there may be instances where no shift is assigned, rendering the ambulance unavailable for the day and unable to participate in incident response.

A shift plan incurs a cost, which we aim to minimize. This cost is determined by the duration of the shift and the associated cost of the ambulance type.

In evaluating the performance of a shift plan, we measure its effectiveness in handling a set of incidents. This set represents the spatial and temporal distribution of incidents that occur within a day. We can obtain such incident sets through two main approaches.

The first approach involves leveraging historical data, which document the occurrence of incidents in a given area over months or years. By uniformly sampling a representative subset of this data, we can test the generated shift plan's performance. This approach assumes that past incident patterns will persist in the future. Historical data provide the most reliable means of simulating incident occurrences accurately.

The second approach involves defining a distribution that generates incidents based on prior knowledge. For instance, we may observe that incidents primarily occur during early mornings, around lunchtime, or at transportation hubs due to commuting patterns. Conversely, we may notice a lower incidence rate during nighttime compared to the daytime.

While the first approach more accurately depicts the occurrence of incidents in the area of interest, obtaining such historical data can be challenging and time-consuming. Moreover, these data often remain confidential, making it difficult to access them, for example from other EMS organizations.

Therefore, for the purposes of this thesis, we will adopt the second approach, generating representative incident sets using a predefined distribution. This approach offers greater flexibility, allowing us to experiment with different distributions and simulate various scenarios, including unexpected or extreme situations.

Finally, with all this information at our disposal, we can now shift our focus towards evaluating the performance of the shift plan against a set of incident sets. In order to measure performance, we will assess the ratio of successfully handled incidents to the total number of incidents in the set. A higher number of handled incidents and lower costs indicate a better shift plan. While this approach is reasonable, we will take a slightly different route in this thesis. Since this thesis is associated with the Computer-Aided Dispatch System Organization Logis Solutions s. r. o. (Logis), which employs advanced solutions for existing EMS, Logis has the advantage of having historical incident data sets available. This leads us to examine the success rates achieved by each incident set on a given day. As the proposed solutions in this thesis may be utilized in the production software developed by Logis for their EMS clients, it would be ideal to generate a shift plan that maintains or surpasses the success rates indicated by the historical data, while concurrently reducing costs. Therefore, the success rate will be provided for each incident set, and our optimization will solely focus on minimizing the cost.

Introducing the concept of success rate provides a useful framework for considering a shift plan as either valid or invalid. A shift plan is deemed valid if it can meet the given success rate, indicating its ability to satisfy the incident requirements. Conversely, a shift plan is considered invalid if it fails to meet the specified success rate. It is worth noting that there may be scenarios where no shift plan can handle the incidents to meet the desired success rate, resulting in all shift plans being invalid. However, this particular case is not our primary concern, as the success rates derived from historical data are based on shift plans employed on previous days, which were not necessarily designed using highly sophisticated methods. Therefore, the probability of encountering such a situation in high-quality historical data is very low. Nonetheless, even in such scenario the proposed solutions will prioritize maximizing the success rate to the greatest extent possible.

1.2 Evaluating success rate of a shift plan

Our primary objective is to ensure that the evaluation of the shift plan closely reflects real-world conditions. It is essential that the success rate of a shift plan, as determined by a given incident set and specific ambulances, closely aligns with its real-world performance. To achieve this, we will employ evaluation strategies that mirror those used in actual ambulance dispatching.

The most direct and flexible approach is to develop a simulation that emulates the real-world dispatching of ambulances to incidents based on the shift plan. This simulation will also incorporate the handling of incidents at the occurrence location, as well as the travel to the hospital and return to the depot. In reality, ambulance dispatching decisions are guided by a set of rules. While these rules can become quite complex, often requiring approval from a dispatcher, we can devise our own rules that closely approximate real-world dispatching practices. By doing so, we can ensure that the probabilities of dispatching in the simulation closely mirror those in the real world and are easier to work with and simulate. Leveraging Logis's extensive expertise as one of the top CAD dispatchers in the market, Logis has derived the following abstracted rules. If multiple ambulances satisfy a given rule, the selection process will follow the subsequent rules in the specified order.

(1) Rule of Availability: Give priority to ambulances that are free, either stationed at the depot or returning from a hospital after completing an incident.

(2) Rule of Promptness: Prioritize the ambulance with the earliest estimated arrival time to the incident scene.

(3) Rule of Workload Distribution: Favor ambulances with the least overall active time, ensuring a fair distribution of workload among all available ambulances.

(4) Rule of Cost: If multiple ambulances can handle an incident equally well, choose the one with the lowest operating cost.

(5) If still more than one ambulance satisfies all the above rules, just choose one at random. In real life, this will be dispatcher's choice.

In addition to the previously mentioned rules, before selecting the best ambulance for an incident, we must ensure that the ambulance satisfies a set of conditions. These conditions determine whether a particular ambulance is capable of handling the incident. The conditions are as follows:

(1) Time for Response: The ambulance must have sufficient time to travel from its current location to the incident within the maximum response time specified for the incident type.

(2) Duration at Incident: The ambulance must have enough time available to remain at the incident location for the expected duration, which is also determined by the incident type.

(3) Travel to Hospital: Sufficient time must be available for the ambulance to travel from the incident location to the nearest hospital.

(4) Patient Delivery: The ambulance must have enough time to transport the patient to the hospital, considering the specific duration required based on the incident type.

It is crucial to ensure that the assigned ambulance can complete all the necessary tasks outlined above within the allocated shift interval. By verifying these conditions, we can determine the suitability of an ambulance for a given incident, ensuring that it has the required time to carry out its responsibilities effectively.

It can happen, that no ambulances can handle given incident based on above conditions. In such a case, the incident is declared as unhandled, and the success rate ration must be updated appropriately. This incident is therefore ignored and no action is done.

Once the best ambulance is selected, the incident is assigned to that ambulance, and the ambulance proceeds with handling the incident.

In the simulation, all incidents from the incidents set are processed sequentially, one by one, and the best ambulance is selected solely based on the above rules and conditions. Evaluating the incidents one by one closely resembles the functioning of a shift plan in the real world, not exploiting the bigger picture but only deciding on local information.

The accuracy and quality of the success rate obtained from the simulation are heavily influenced by the calculated durations for various stages of incident handling, including ambulance response time, incident handling at the scene, patient transfer to the hospital, handling of the incident at the hospital, and the estimated time required to return to the depot. To accurately calculate these durations, a reliable distance calculator is essential.

One approach to achieve this is by discretizing the area of interest and precalculating the distances for all pairs of locations, storing them in a distance matrix. When a distance request is made, the distance calculator simply retrieves the precalculated distance for the requested locations. The time required can then be calculated using the velocity of the ambulance. However, it is important to note that this approach does not consider factors such as traffic or the type of route taken. A more appropriate approach might be to precalculate not the estimated distance but the estimated duration, which also eliminates the need for the ambulance's velocity information. To obtain reasonable precalculated duration, Here or Google map services might be great candidates. These durations can also be recalculated to better incorporate these factors, such as traffic condition or road closure etc ...

Another factor to account for which might negatively influence the quality of yielded success rate is that the variability of durations in real-life scenarios vary. Factors such as traffic conditions, road closures, and unexpected events can cause variations in ambulance response times, incident handling durations, and patient transfer times. Therefore, because these durations may vary in the real world, introducing stochastic factors to simulate their variability could lead to improvements in estimating the success rate. Despite that, given the necessity of running the simulation multiple times, it is more crucial to ensure that the simulation effectively captures real-life scenarios. Introducing additional stochastic elements may also introduce unnecessary unpredictability to the simulation. Therefore, for the sake of efficiency and reliability, the simulation does not incorporate such stochastic factors.

1.3 Problem formalization

As the problem above is described, it is clear we have to find the most optimal shift plan s_o from set of all possible shift plans S^T, where T is a set of allowed time intervals, against given incident sets I. Most optimal means it has to be valid,

$$\text{successRate}(s_o, I) \geq \text{givenSuccessRate}(I),$$

and has the least possible cost over all valid shift plans S_v,

$$\forall s_v \in S_v : \text{cost}(s_o) \leq \text{cost}(s_v),$$

defined,

$$S_v = \{s_v \in S^I | \text{successRate}(s_v, I) \geq \text{givenSuccessRate}(I)\}.$$

If there doesn't exist any shift plan in S^I which satisfies given success rate, the most optimal is then the shift plan with the highest success rate and at the same time having the least cost. Let denote

$$S_r = \{s_r \in S^I | \text{successRate}(s_r, I) \geq \text{successRate}(s, I), \forall s \in S^I\}$$

as a set of all shift plans with the highest success rate. The optimal $s_o \in S_r$ is now defined as:

$$\forall s_r \in S_r : \text{cost}(s_o, I) \leq \text{cost}(s_r, I).$$

Note, that this definition of optimal shift plan allows for multiple optimal solutions. We can therefore denote set of all these optimal solutions as S_o.

1.4 Exhaustive solution

The most straightforward algorithm for finding the most optimal solution is to exhaustively enumerate over all possible shift plans by brute force, holding some global best shift plan so far and updating it in each iteration against current shift plan. After going through every possible shift plan we can then be certain that we have found the most optimal one.

Algorithm ExhaustiveSolution
Input: I^T, givenSuccessRate(I^T)
Output: s_o
bestSoFar $= s_1 \in S^T$
for $i \in \{1, 2, ..., |S^T|\}$ **do**
  if condition is true **then**
    Perform some operation
  else
    Perform a different operation
  end if
end for
while condition is met **do**
  Do something
end while
Return final result

2. Proposed solutions overview

Conclusion

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A. Attachments

A.1 First Attachment