Emergency Response Simulation

Hung H. Nguyen

CS166 - Fall 2019

Minerva Schools at KGI

I, Introduction

In any city, it is important to have an efficient emergency response system, so that ambulances are promptly dispatched to patients. Therefore, city officials need know how to allocate the limited number of ambulances so that they are able to cater to this need. This report will model the scenario using networks and object-oriented programming, and it will compare between different strategies for ambulance placement using Monte Carlo simulation results. For this report, we will focus on the city of Hanoi and use the simulation to generate specific recommendations for the city.

II. Assumptions

The map of Hanoi is represented by a network and every node is a district (Vietnamitas en., 2011). An edge will connect two adjacent districts. Each node has a probability *p* to indicate how likely that an ambulance call comes from that node. For Hanoi, we assume that *p* has a linear relationship with the population density of each district; the higher the density, the higher *p* will be (Appendix). The linear assumption is not entirely accurate because the relationship could be otherwise, but for the purpose of this simulation, the assumption is sufficient. Additionally, each edge has a weight *w* to show the travel time (in minutes) between two nodes. By using Google Maps, this report estimates the travel time between two districts by assuming the time is equal to travel time by car from the center of one district to the center of the other district. From this assumption, it follows that an ambulance station will be placed in the center of its home district.

There are two main parameters: the number of ambulance stations *S*, the total number of ambulances *A*. The higher *S* and *A* are, the more the city will be able to cater for emergency calls. For simplicity, we assume that each district can have at most one station, and each station must have at least one ambulance. Realistically, Hanoi can only afford a limited number of stations and ambulances. Therefore, the placement of stations and the allocation of ambulances to each station are subjects of different strategies that our simulations will compare.

The simulation measures three main metrics: the response time to an ambulance call, the outstanding number of ambulance calls per time step, and the number of idle ambulances per time step. The first two metrics are somewhat correlated; if the response time is low in general, then it is likely that the number of outstanding emergency calls is low as well. The reverse is also true. The last metric is included to measure the level of redundancy of each strategy. If there is a limited number of ambulances, it is important to balance between redundancy and actually using ambulances to serve emergency calls. We also assume that a call automatically goes to the nearest station on the map.

III. Simulation Rules[1]

At every time step, the simulation follows these rules:

1. At a certain interval *I*, loop through every node and generate a call based on the probability *p* of each node. If there is a call, send it to the nearest station using breadth-first-search. For example, if *I* = 5, every five time steps, new calls will be generated. The inclusion of the interval is to ensure that the number of incoming calls is reasonable. Through experimentation, it is found that if calls are generated at every time step, it would take an unrealistic amount of resources (stations and ambulances) to deal with them effectively.

[1] #algorithms: I extensively used object-oriented programming in this project in order to break down a complicated scenario into easy-to-understand chunks of code. I also used suitable data structures to increase efficiency (double-ended queues to accept requests, heaps to store ambulances).

2. Go through all the stations. For each remaining request in each station, dispatch an ambulance from the station if there is any available. When an ambulance is dispatched, its timer will be updated to be equal to twice the total one-way travel time (because the ambulance must return to the station) plus a random factor to account for varying treatment times. An ambulance can only be dispatched again if its timer is zero, in other words, if it has returned to the station.

3. At the beginning of the next time step, the timers on all dispatched ambulances are decreased by 1 if they are positive, and the waiting times of all outstanding (unserved) calls are increased by 1.

4. To record the response time to an ambulance call (different from the *timer* on the ambulance itself), when an ambulance is dispatched, the response time is given by $max(D, t_R + D)$, where D is the *one-way* travel time to the call location that includes the random factor and t_R is the amount of time the caller has waited since he/she called. If the call is immediately responded to, $t_R = 0$, so the response time is D. If there is a backlog of requests at the time the call happened and it cannot be served right away, $t_R > 0$, so the response time is now $t_R + D$

5. To attain the number of outstanding requests, at each time step, record the number of unserved calls at each station.

6. To attain the number of idle ambulances, at each time step, record the number of ambulances with a zero timer.

IV. Strategies

This report compares three strategies for placing stations and distributing ambulances:

- Strategy 1: Place stations at the riskiest districts (nodes with highest *p*) and equally distribute the total number of ambulances to each station. If there are any left-over vehicles after dividing, place them all in the riskiest node.
- Strategy 2: Place stations at the riskiest districts and preferentially distribute ambulances to each station based on how risky each station's location is. For example, stations situated in more risky locations will, on average, get more ambulances than stations in less risky locations.
- Strategy 3 (baseline strategy): Place stations randomly and distribute ambulances similar to Strategy 1.

The rationale behind placing stations at nodes with the highest *p* values first is so that stations can respond immediately to calls from these locations (according to the assumptions described in Part II), thus the average response time to a call and the number of outstanding calls are both minimized. Even though Strategy 3 is expected to be the most inefficient, it can still be insightful to include it to serve as a baseline. In contrast, Strategy 1 and 2 serve as a comparison between equal ambulance distribution and preferential ambulance distribution as an attempt to minimize the number of idle ambulances.

V. Results and Analysis

In order to compare the performance of these strategies, we ran a Monte Carlo simulation for every single reasonable combination of parameters and strategies, assuming that:

1. Number of stations: (min, max) = (1, 6). This satisfies the original assumption that not every district has a station.

2. Number of ambulances: (min, max) = (6, 25). The minimum is chosen so that every station has at least 1 ambulance. Through experimentation, it is found that above 25 ambulances, there is not any significant increase in strategy performance. In addition, 25 is also chosen for the sake of simulation running time.

Combined with three strategies, that results in 3 x 6 x 20 = 360 combinations possible. For the sake of actual running time, only 100 Monte Carlo trials for each permutation were executed. For each permutation, after 100 trials, data for the three metrics associated with that permutation are collected.

The most important metric regarding the context of this model is response time to an emergency call. Therefore, it will serve as the first criterion to compare between these strategies, while other metrics will serve as supporting evidence. Fig. 1, 2, and 3 illustrate how the three strategies perform regarding this metric.

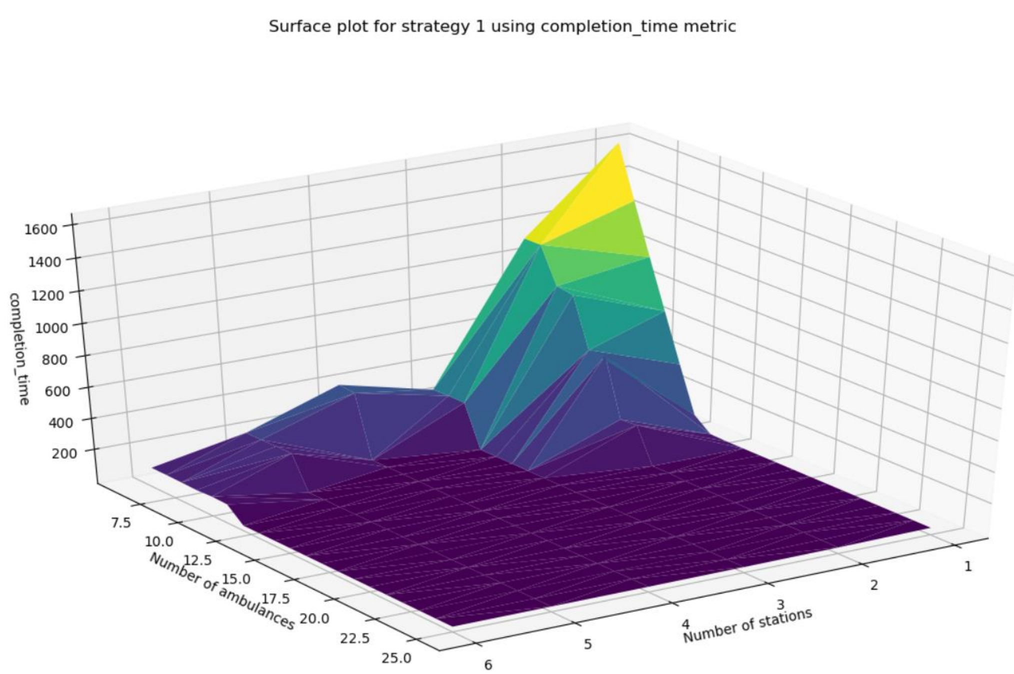

Figure 1. Surface plot illustrating the performance of Strategy 1 using response time as the metric[2]

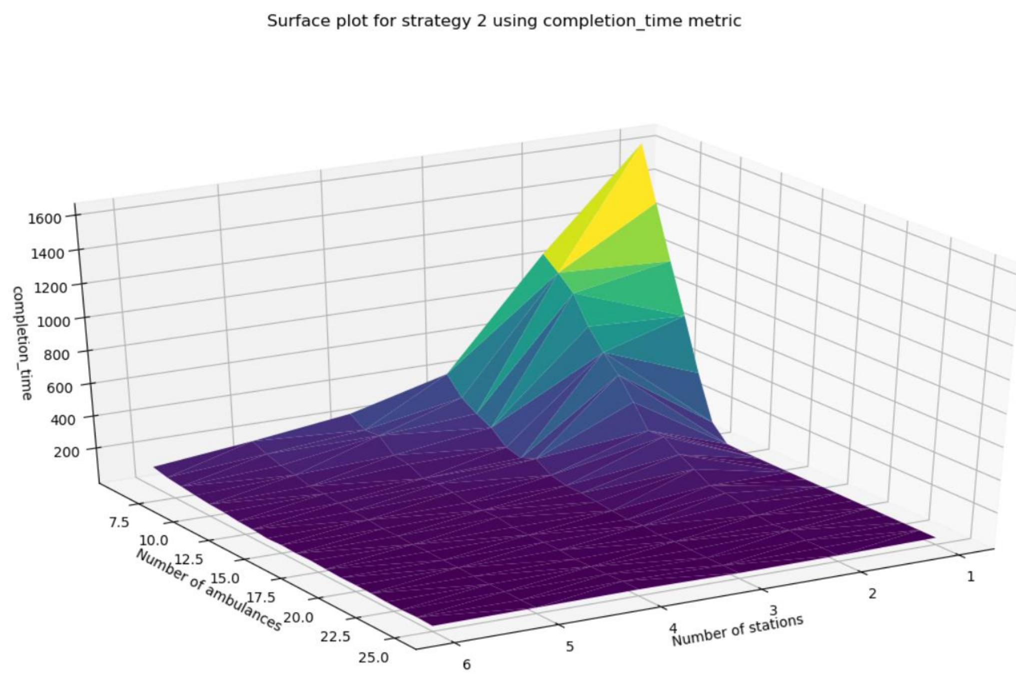

Figure 2. Surface plot illustrating the performance of Strategy 2 using response time as the metric

[2] #dataviz: I generated several 3D plots that made it very easy to comprehend the performance of each of the proposed strategies.

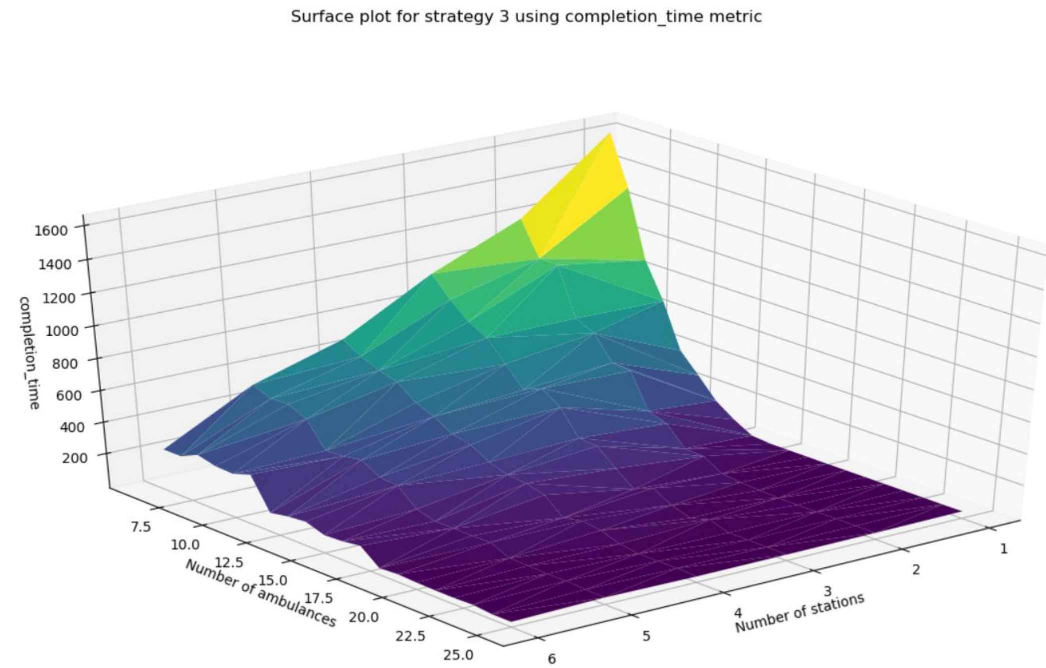

Figure 3. Surface plot illustrating the performance of Strategy 1 using response time as the metric

The common trait between all three strategies is that when more resources (stations and ambulances) are added, every strategy performs better. This is observed in the figures, as there are downward slopes towards the direction of positive x and y axis in all figures. This is as expected, as per our assumption in Part II.

However, Hanoi does not have unlimited resources, so it comes down to which strategy performs the best with the least amount of resources. To simplify the analysis, let’s assume there is a standard emergency response time X that Hanoi city officials would like to meet. Depending on what X is, with each strategy, we take the smallest combination of resources that would produce the standard response time and compare that combination with those of other strategies. The most effective strategy would perform to that standard using the least amount of resources.

Given the traffic data of Hanoi gathered in Part II, it is reasonable for $X \sim 10$, or 10 minutes. With this standard, the most effective combination from each strategy is as follows:

Strategy	Number of stations	Number of ambulances	Avg. Response time (minutes)	Avg. Outstanding calls	Avg. Idle ambulances
1	4	14	9.409710	0.109110	10.215483
2	6	25	10.996259	0.575093	21.8882
3	6	24	9.080885	0.033956	20.313160

Table 1. The most efficient combination of stations and ambulances for each strategy so that the response time is at least 10 minutes.

The results show that Strategy 1 is the most effective strategy, being able to deliver a 10-minute response time with fewer resources than both Strategy 2 and 3. Strategy 1 is also effective in terms of the other two metrics as well. With only 4 stations and 14 ambulances, the number of average outstanding calls are very comparable to those of the other two strategies, while the average number of idle ambulances is vastly better.

Interestingly, notice that Strategy 2, which is expected to perform better than Strategy 1 because it preferentially places more ambulances in higher risk stations, actually performs the worst in terms of all three metrics when the requirement is $X \sim 10$. There can be two reasons for this. First, while Strategy 1 is deterministic – always places stations and allocates ambulances *the same way* every time, Strategy 2 has randomness *in the process* of distributing ambulances (in implementation) and Strategy 3 has randomness *in the process* of placing stations (in implementation). Therefore, with the condition that the average expected response time is closest to 10 and that both Strategy 2 and 3 responded by using almost all of the resources allowed in the simulation, it could be that strategy 3 performed better by chance. In fact, when fewer resources are used (with no condition for X), we notice from all the above figures that Strategy 2 has a similar pattern as Strategy 1 and is better in general than Strategy 3.

Because there is this factor of chance, it could be that for only 100 trials in the Monte Carlo simulation, the spreads of the distributions are not narrow enough to fully differentiate between strategies. In this context, because every metric unit (time, request, ambulances) can make a difference for patients in real life, *narrowness* is roughly defined has a 95% confidence interval such that the left and right cutoff is no more than 0.5 units away from the mean. With 100 trials, all metrics for Strategy 1, shown in Fig. 4 (Appendix), satisfy the requirement, as expected due to its deterministic nature. However, for Strategy 2, the expected response times distribution in Fig. 5a (Appendix) did not meet the requirement due to some potential outliers. The same can be said for the distributions of expected response times and expected number of idle ambulances, shown in Fig. 6a and 6c (Appendix), for Strategy 3.

Therefore, the choice of 100 trials is potentially a limitation of this analysis. To improve in the future, we can improve the efficiency of the implementation, so that the Monte Carlo simulation can accommodate more trials. In the best case, 1000 to 2000 trials would be ideal.[3]

VI. Recommendation

Based on the analysis of the proposed strategies, for the time being, it is recommended that the city of Hanoi should follow Strategy 1 to get the most value out of its resources. In summary, Strategy 1 suggests that the city should identify districts with the most ambulance calls and prioritize placing stations there, then equally dividing ambulances to each station. Depending

[3] #modelling: I thoroughly constructed a model from scratch to simulate the emergency response scenario, clearly clarified all of my assumptions, made aware of a limitation, and suggested several potential improvements.

on what the minimum required response time is, a different set of resources are needed, but it should still provide the most value.

The model provided in this report is also extendable, such that if there are any new deployment strategies that city officials would want to test, they can do so with this framework. A potential avenue for future research is a strategy that automatically reallocates ambulances based on usage. Currently, the number of idle ambulances for effective sets of resources are still quite high. It would be interesting to test whether reallocating ambulances dynamically would decrease this metric, while maintaining good performance in response time as well.

Appendix

1) Relationship between p and district population density

Density data used in the code is gathered from Phung (2018) and rounded up for simplicity. Assume that $p_{min} = 0.2,\ \ p_{max} = 0.8$. Map p_{min} to the lowest density and p_{max} to the highest density. Map all other density values to p values by fitting them to this linear line accordingly (see code).

2) Distributions for different metrics for all three strategies (figures shown here is different from figures shown in Jupyter Notebook)

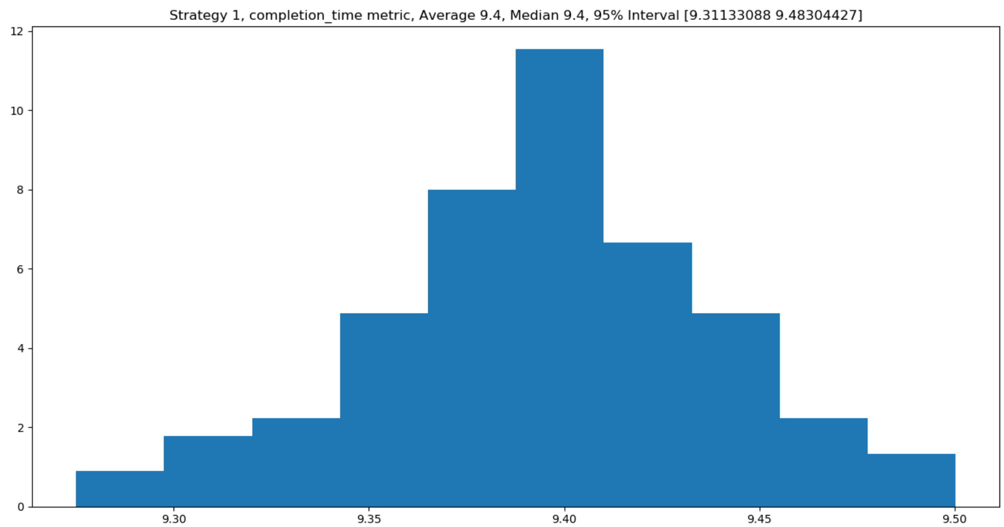

Figure 4a. The distribution of expected response time for Strategy 1 with the number of stations and ambulances following Table 1, with 95% confidence interval.

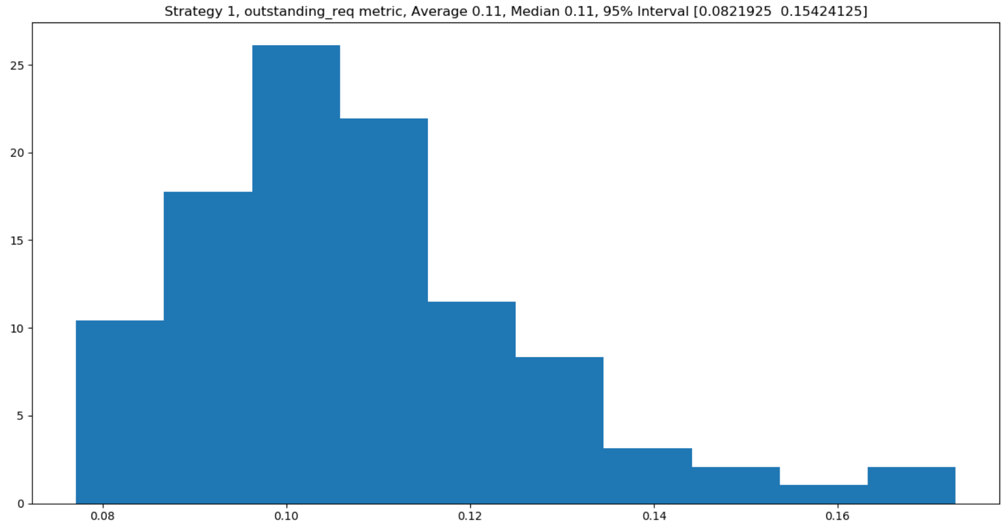

Figure 4b. The distribution of expected outstanding request for Strategy 1 with the number of stations and ambulances following Table 1, with 95% confidence interval.

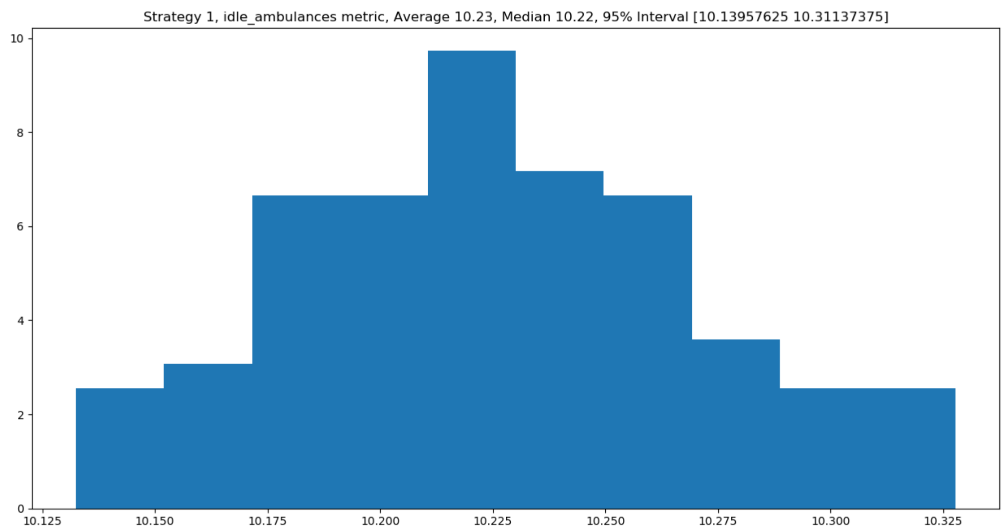

Figure 4c. The distribution of expected idle ambulances for Strategy 1 with the number of stations and ambulances following Table 1, with 95% confidence interval.

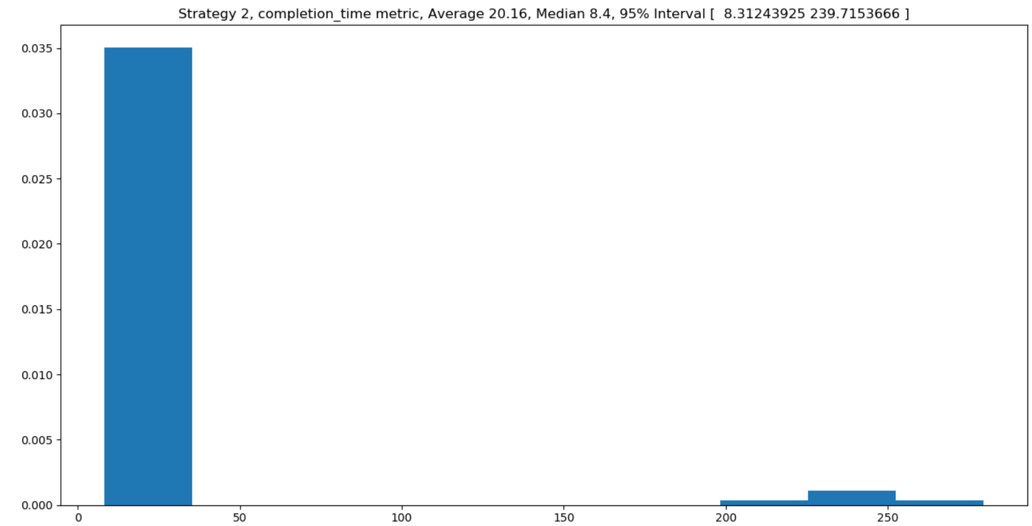

Figure 5a. The distribution of expected response time for Strategy 2 with the number of stations and ambulances following Table 1, with 95% confidence interval.

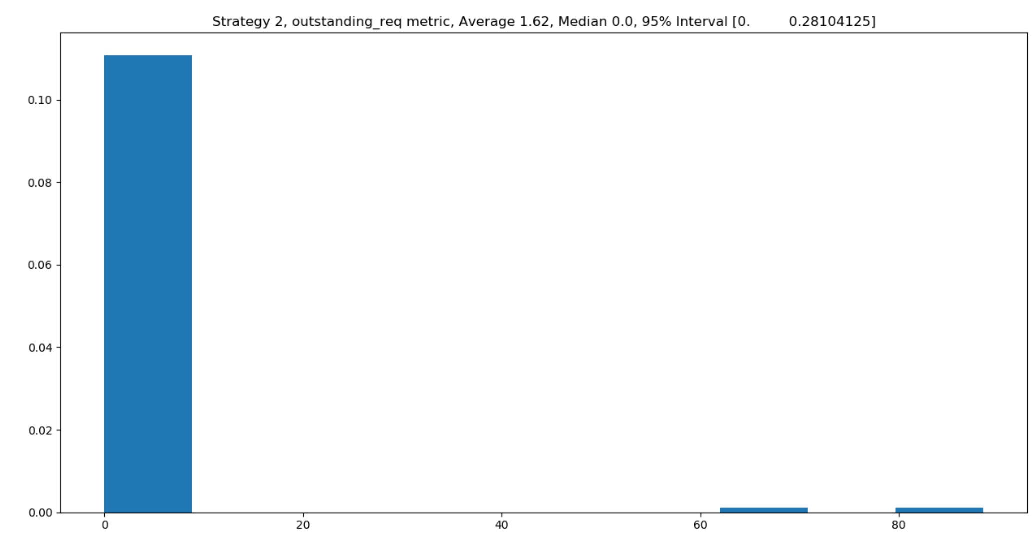

Figure 5b. The distribution of expected outstanding request for Strategy 2 with the number of stations and ambulances following Table 1, with 95% confidence interval.

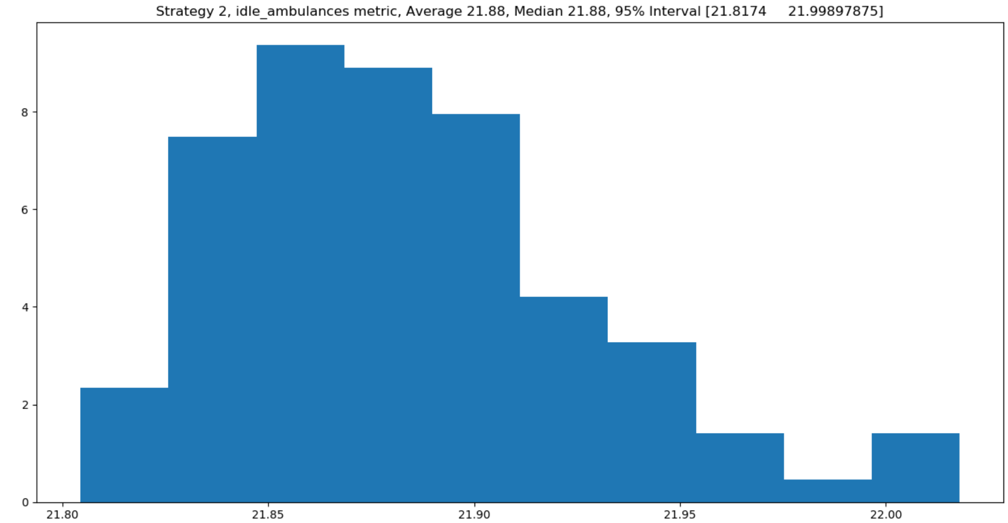

Figure 5c. The distribution of expected idle ambulances for Strategy 2 with the number of stations and ambulances following Table 1, with 95% confidence interval.

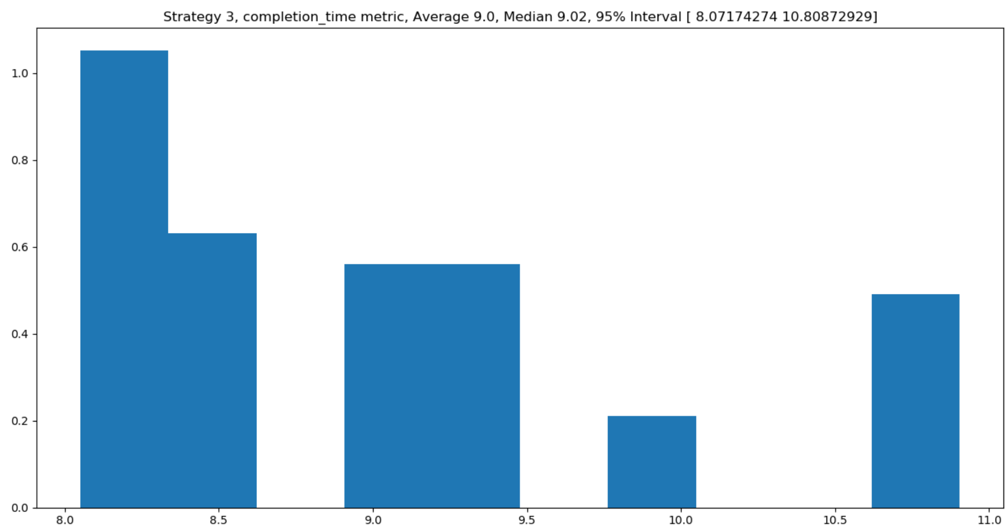

Figure 6a. The distribution of expected response time for Strategy 3 with the number of stations and ambulances following Table 1, with 95% confidence interval.

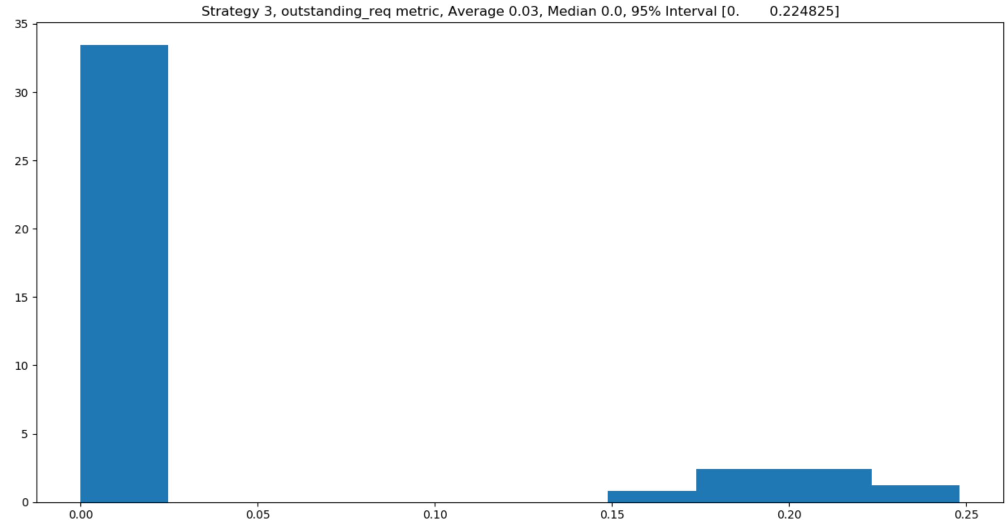

Figure 6b. The distribution of expected outstanding request for Strategy 3 with the number of stations and ambulances following Table 1, with 95% confidence interval.

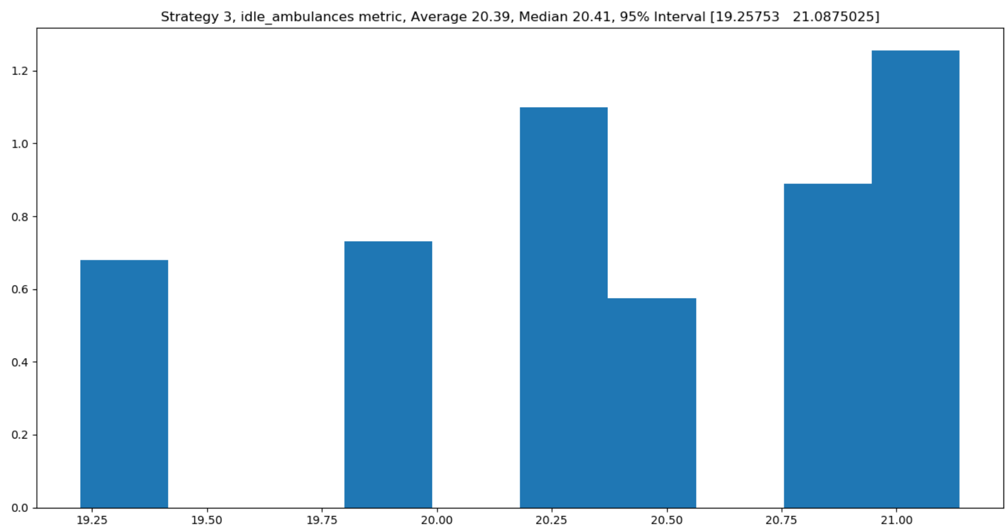

Figure 6c. The distribution of expected idle ambulances for Strategy 3 with the number of stations and ambulances following Table 1, with 95% confidence interval.

References

Phung, N. (2018, July 25). A Guide to Hanoi's Districts: Navigating Vietnam's Capital. Retrieved December 18, 2019, from Vietcetera website: https://vietcetera.com/en/a-guide-to-hanois-districts-navigating-vietnams-capital/

Vietnamitas en. (2011, April 13). Map of Hanoi Vietnam's capital—Vietnam. Retrieved December 14, 2019, from https://en.vietnamitasenmadrid.com/2011/04/hanoi-vietnam-map.html