Agent-Based Modelling of Earthquake response in Turin, Italy

SEN1211 - Agent Based Modelling - Model assignment

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Group 63

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1. Introduction

Preparing cities in critical areas for disaster is an ever relevant topic. One of these is earthquake emergency response. With 2262 (*Number of Earthquakes Globally 2000-2021*, n.d.) earthquakes of magnitude 5 or higher around the globe and one of 5.5 or higher occurring in Italy (*Seismic Activity in Italy*, n.d.) Italy is a country where precautions are necessary. Turin, at the foot of the Alps, is such a city where designing emergency response and rescue is necessary as it lies in the medium risk zone of Lombardy (*Earthquake Risk in Italy*, n.d.). The objective of this research is to present a policy that was found best to reduce fatal casualties in the case of an earthquake in Turin.

As such, for this project the event of an earthquake on the city was simulated using agent-based modelling. At first a basic model was constructed to simulate the current city of Turin and measure the effect of an earthquake on the current city and the functioning of its emergency response became clear. To construct the model research was done on Turin to fulfil a correct parametrization. This gave a benchmark through multiple variables based on residents, general building damage, general road damage, (performed) healthcare et cetera. The effect of multiple policies like first aid training and expansion of ambulance fleets and hospitals on these variables was measured to measure their effectiveness. For this research the following research questions were formulated.

1. What is the behaviour of the model under various parametrizations, and how does it relate to the reality of emergency response?
2. What is the influence of first aid training and the extension of hospitals and ambulances on the effectiveness of rescue operations?

2. Conceptual model

2.1 Description of Software Model

This software model was designed to model the response of the emergency services of Turin to an Earthquake in Python. The structure of the model is as follows: In the setup stage, a specified number of large buildings undergo a check to see if they are undamaged, lightly damaged, or collapse. Each building is placed at a random node in the city; any road attached to a collapsed building has a fixed probability of being removed, modelling the potential of debris to block roads.

In the case of damage or collapse a (smaller or larger, respectively) number of wounded "resident" agents are spawned. They are randomly assigned a "woundedness" between 0.0 and 10.0, which gradually increases over time (or decreases if in a hospital), until the agent dies upon this parameter surpassing 10.0 (or is remitted from medical care upon decreasing below 0.0); the agents are placed at a random node corresponding to where the building was.

Ambulance agents are the only agents which move around the map; they attempt to find the nearest wounded resident, drive to their location, pick them up (and any other agents at the same node, up to the ambulance's capacity), and transport them to the nearest hospital. Agents in the ambulance take no damage, to model the stabilising care given by EMTs en route.

Hospital agents are responsible for maintaining a list of current patients, and at each timestep, healing each of them at a fixed rate. The hospital has a limited capacity modelled by its number of total beds; an over-capacity hospital cannot receive new patients, but those patients above the limit will be 'stabilised' (i.e. will not have an increasing woundedness), but also will not be healed until beds are available - this is meant to loosely model the hospital's triage procedure.

2.2 Parameter Description and Selection

Within this section, the principal parameters of importance are presented. Hereby are a few technical ones governing the simulation not presented, but may be found in the code, in which the curious reader is directed to look for more detail regarding any of the above as well.

1. It is assumed that the city has 300 large buildings, based on a comparison to similar data found for Mexico City, scaled for population ("Turin," 2022)
2. The number of hospitals is assumed to be 1, the CTO Turin (i.e., smaller clinics and hospitals are not included, partly because increasing the number of hospital agents is an experiment that is wished to perform, and partly due to the difficulty of finding data) ("Turin," 2022)
3. Both the capacity of the hospitals and the number of ambulances is based on per-capita data for Italy provided by the WHO, scaled by the city's population (and an additional urban-concentration factor, modelling the tendency for medical care to be more concentrated in cities than on average). (*Hospital Beds (per 10 000 Population)*, n.d.)
4. The number of residents in each building is assumed to be distributed according to a Pareto distribution (with shape parameter 1.16 corresponding to the '80-20' rule, and size parameter to make the mean equal to the population divided by the number of buildings). The Pareto distribution is used to model the fact that people tend to congregate in buildings, with more

populous buildings exerting more attraction; for the selected parameters, the variance of the Pareto distribution is not defined, and so representations of the absolute number of residents harmed (as opposed to the effect of their spatial distribution) should be used with hesitation.

5. Agents are assumed to take six hours to die from injuries, and two hours to be healed in the hospital (for both, scaled according to the agent's initial woundedness); these parameters are not set based on data, but by the authors' estimation of their values, given that reliable data is not available due to the 'woundedness' parameter's artificiality.
6. It is assumed that lightly damaged buildings cause 10% of the injured agents as collapsed ones (again, set arbitrarily).
7. Ambulances are set to move at a speed of 30 m/s, and have a capacity of 3 wounded agents.
8. The base magnitude of the earthquake is richter magnitude 6, occurring roughly 70 kilometres to the Southwest of the city.

2.3 Mathematical Notes

The damage done to buildings was calculated per the specification in the manual; however the decay of the earthquake magnitude with distance was set to follow the more realistic profile given by the Lillie formula ("Richter Magnitude Scale," 2022) this entailed translations between the specified 'EM' scale and the traditional Richter scale. Building height and construction-material were drawn from two discrete, independent probability distributions set arbitrarily.

2.4 Outcomes of the base model

When the base model is run, four plots can be analysed: the fraction of dead residents, the fraction of healed residents, the ambulance occupancy fraction and the hospital occupancy fraction, in figure 2.1 below. For every plot, the X-axis is the elapsed time since the Earthquake in minutes. All Y-axes are fractions. Please note that for computational tractability, all simulations were performed at a 1:5 scale; thus the actual number of residents healed or dead should be five times that is shown - all data is shown in fractions, so the effect of this coarsening is expected to be minimal.

Furthermore, the rapid fluctuation of the ambulance occupancy is a result of the fact that the ambulances move very quickly, and almost always reach their target within the five-minute timestep; though this represents the introduction of some accuracy, running the simulation at a shorter timestep was infeasible, and the 'lost time' of the ambulances plausibly corresponds to the time taken in loading and unloading passengers. Finally, while the scale of each variable was kept between zero and one for ease of comparison, this renders some of the plots difficult to read - to ameliorate this, rescaled sample trajectories of each variable and for each policy are presented in the appendix.

In the base case, we observe that nearly all wounded civilians die, and extremely few are saved. The high ambulance occupancy and low hospital occupancy indicates that decreasing transport times should result in saving more lives.

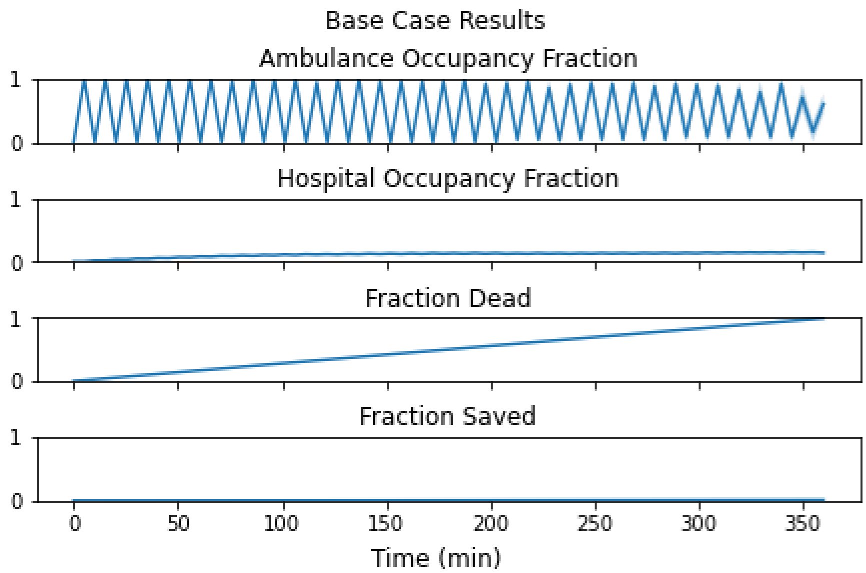

Figure 2.1: Base Model results in fractions

2.5 Implemented policies

In order to decrease the number of deaths and increase the number of healed residents, three policies are going to be implemented within the model.
The first policy will be that civilian cars are assigned as ambulances to transport the injured people from collapsed buildings to hospitals. Therefore, there are ten times more ambulances usable during the aftermath of this earthquake, which resulted in a total amount of 250 ambulances after the implemented policy.
Secondly, churches, middle and high schools will be used as a hospital within the city. Hereby, ambulances can transport more injured residents to closer hospitals, due to the decreased travel time towards a hospital. The total number of hospitals is multiplied with ten, which gives in total 10 hospitals in the city. It is assumed that the hospital dispatches many of its workers to these new sites, so that both the healing effectiveness and the total treatment capacity remain the same.
And lastly, people have to heal injured people in all the newly created hospitals. Therefore, firefighters undergo first aid training in order to be assigned as trauma doctors. By this policy, the healtime of an injured resident will be accelerated by four times, taking between 0 and 1.5 hours to heal, depending on the woundedness upon admission to the hospital.

2.6 Hypotheses

The purpose of this agent-based model is to understand the qualitative effect of changing the model parameters in order to inform policy recommendations to the city of Turin, for responding to an analogous disaster. Thus, different experiments have to be performed, predicting in advance the effect of given parameter-changes for scientific utility. All results are presented as the average over 5 runs (any more induced ‘out-of-memory’ errors) - plus-or-minus one standard deviation of these averages is lightly shaded, but is mostly small enough to be invisible, indicating a high degree of consistency.

3. Software implementations

3.1 Results of the experiments

Experiment 1: Civilian car commandeering

Given the high number of deaths, and low occupancy fraction of the hospital, it is predicted that having ten times the number of ambulances will save approximately ten times the number of citizens (i.e., the present number of ambulances is so deficient that no saturation effects are observable). The observed result can be seen in figure 3.1 below.

In contrast to the base case, the hospital occupancy is now nearly unity; the prediction of a tenfold increase in lives saved approximately holds (see quantitative data in the table in Section 3). However, further ambulances would need to be supplemented by an expanded hospital system in order to effectively save lives.

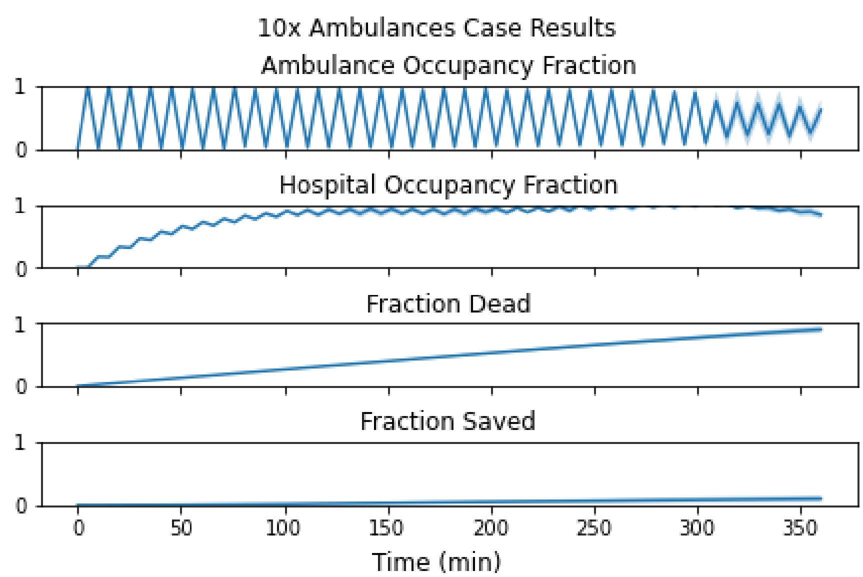

Figure 3.1: Experiment 1 results in fractions

Experiment 2: Churches and schools are used as hospitals

Given the low hospital occupancy fraction in the base model, it is predicted that having ten times the number of hospitals (with the same total number of beds) will increase the number of saved citizens, but by less than a factor of two (the ambulance occupancy is the percentage of time ambulances are occupied - in the base model, this is nearly 0.5, the maximum allowed average given that ambulances take a minimum of one timestep to reach wounded residents). The observed result can be seen in figure 3.2 below.

As expected, spreading out the hospital beds and staff over a wider number of locations exhibited minimal effect on the number of citizens saved - in the base model, ambulances practically always managed to travel between hospital and wounded within a timestep, and this remains essentially true in the altered case.

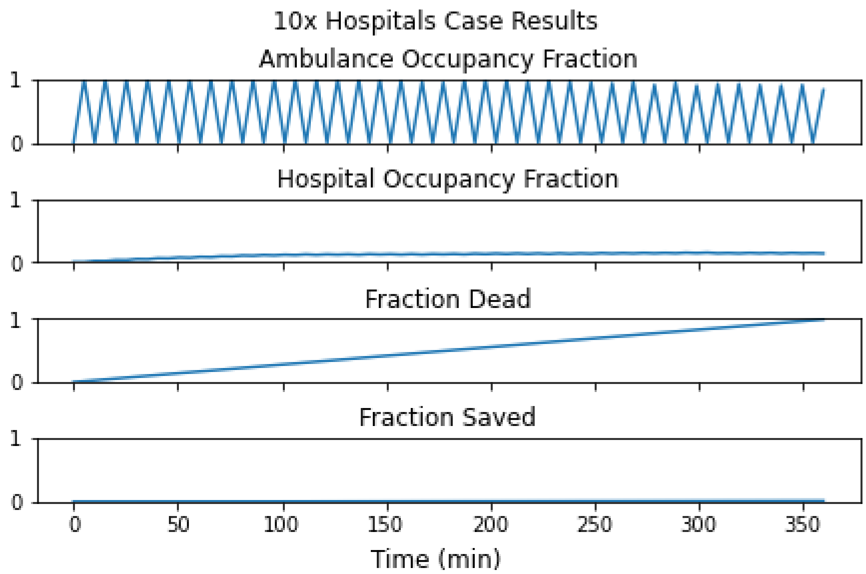

Figure 3.2: Experiment 2 results in fractions

Experiment 3: First aid training for firefighters

Faster healing, due to first aid training for firefighters, would limit the burden on individual hospitals; as the hospital is never close to full in the base model, it is predicted that more rapid healing will have negligible effect on the number of citizens saved. The observed result can be seen in figure 3.3 below.

As predicted, it is observed that faster healing had no substantial effect on the number of citizens saved, as the hospital occupancy is never a limiting factor. It is likely that such an intervention would be a cost-effective way of increasing the effective hospital capacity in cases like Experiment 1, in which this was indeed a limiting factor.

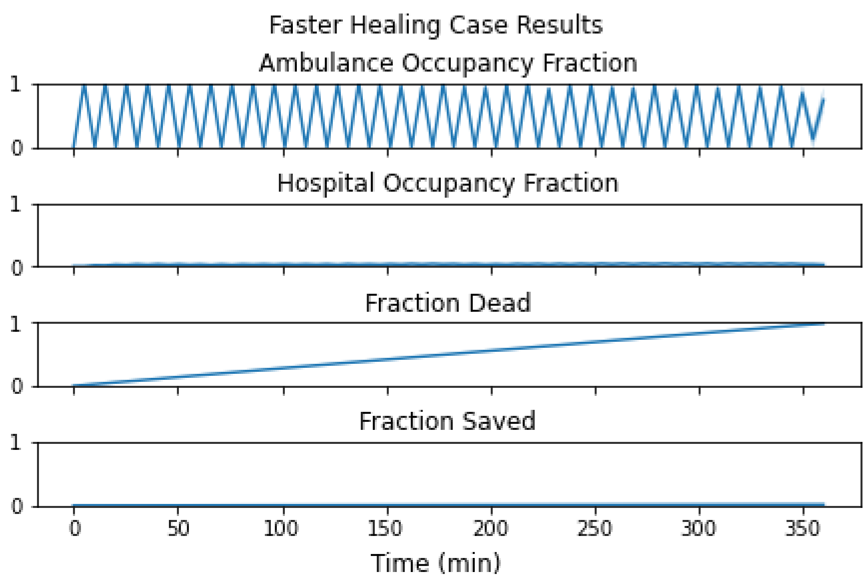

Figure 3.3: Experiment 3 results in fractions

3.2 Comparison of the experiments with the base model

Within this section the outcomes of the three experiments will be compared with the outcome of the base model, shown in paragraph 2.4. For every experiment, a more detailed plot of the number of dead or healed residents and the ambulance and hospital occupancy fractions can be seen in Appendix 6.1 to 6.3. The outcomes of the experiments are in detail described, see below table 3.1. These results are compared with the outcome of the base model.

Table 3.1: Outcomes of the experiments next to the base model in factions

Experiments of implemented policies / results of plots	Base model	Civilian car commandeering	Churches and schools are used as hospitals	First aid training for firefighters
Dead	0.989	0.899	0.989	0.985
Healed	0.011	0.101	0.011	0.015
Ambulance occupancy fraction	0.479	0.481	0.483	0.481
Hospital occupancy fraction	0.110	0.814	0.112	0.031

Overall, the most effective policy - by far - is the augmentation of the ambulance force. As noted above, a ten-times increase in the number of ambulances is sufficient to make the hospital-capacity the limiting factor. In such cases, the faster healing time afforded by trained first-aid responders could also afford a significant improvement in lives saved.

3.2 Verification and Validation

It is necessary to ensure that the model produced is both internally consistent (verification) and meaningfully representative of the reality which it purports to model (validation).

The first step in ensuring consistency of the model is confirming that all relevant results are within the realm of plausibility vis-a-vis reality; as parameters were estimated based on real data, most input data satisfies this criterion, and similarly the output data exhibits a plausible number of wounded citizens (less than the population of the city - generally about 60000 - and more than zero).

Secondarily, in performing the relevant experiments, no parameter-change produced a result which is obviously wrong (e.g. increasing the number of ambulances indeed results in more people being saved). In the absence of observations of the actual result of such earthquakes, the validity of the model cannot be established quantitatively. The primary obstacles to such a verification are the arbitrariness of the factors on which building-collapse depends, along with the associated probability of resident injury, all of which are far more schematic than realistic.

In light of this difficulty, the aim of this report is to use the model to qualitatively predict the dynamics of disaster response given the city's resources - the authors do not believe that the quantitative data gathered, is more than vaguely indicative of the corresponding quantities which would be observed in a real scenario; accordingly, policy recommendations have been formulated on the basis of the qualitative trends seen in carrying out the experiments.

4. Conclusions and recommendation

For this research the various policies in disaster response were modelled for the city of Turin to determine their comparative effects and to provide a recommendation so that Turin (and other cities) are able to prepare better for the case of an earthquake. Three experiments were conducted, simulating the implementation of a variety of these policies, with the intention of reducing casualties in the case of a large-scale earthquake.

These policies were increasing the number of ambulances (by commandeering civilian vehicles), increasing the number of hospitals (by enlisting community buildings, such as schools and churches, to serve as emergency field hospitals, using the same number of hospital workers), and speeding the healing process in the hospital (by conscripting emergency workers with relevant experiences).

The results of these policies indicate that the city is likely deficient in the number of response vehicles needed to respond to a crisis of substantial magnitude - a tenfold increase in ambulances was required in order to make full use of the hospital capacity. On the other hand, increasing the number of hospitals (distributing the hospital resources, and thus the number of beds, between them) showed some effect in increasing the number of citizens rescued, though this effect was minimal. Finally, a more rapid treatment of those in the hospitals exhibited practically no effect on the number of people rescued.

In light of the previous discussion with respect to the limited model-validity, the principal recommendation to the city of Turin is to invest in its fleet of emergency vehicles, either by preparing more ambulances, or drawing up plans to conscript them, either from nearby municipalities or from the ranks of civilian vehicles, in the case of an emergency. Furthermore, if the parameters describing hospital behaviour are reasonably accurate, it is predicted that the city has more than enough hospitals to care for the patients brought in by the ambulances, and thus needn't expend resources on improving their hospital infrastructure for this type of disaster-scenario. An increase in hospital capacity would, however, be useful if the ambulance fleet were to expand so as to make the hospital capacity the limiting factor - in this case, the first-aid training policy is expected to prove a cost effective means of saving more lives when employed in conjunction with the expanded ambulance fleet.

5. References

Earthquake Risk in Italy: The Dangerous Areas - Updated for 2023. (n.d.). ItalyMammaMia.Com. Retrieved January 27, 2023, from https://www.italymammamia.com/earthquake-risk-in-italy.html

Hospital beds (per 10 000 population). (n.d.). Retrieved December 4, 2022, from https://www.who.int/data/gho/data/indicators/indicator-details/GHO/hospital-beds-(per-10-000-population)

Number of earthquakes globally 2000-2021. (n.d.). Statista. Retrieved January 27, 2023, from https://www-statista-com.tudelft.idm.oclc.org/statistics/263105/development-of-the-number-of-earthquakes-worldwide-since-2000/

Richter magnitude scale. (2022). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Richter_magnitude_scale&oldid=1124384787

Seismic Activity in Italy. (n.d.). Https://Quantectum.Com/. Retrieved January 27, 2023, from https://quantectum.com/blog/seismic-activity-in-italy/

Turin. (2022). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Turin&oldid=1121476679

6. Appendices

Appendix 6.1: Plots of implemented policy: Civilian car commandeering

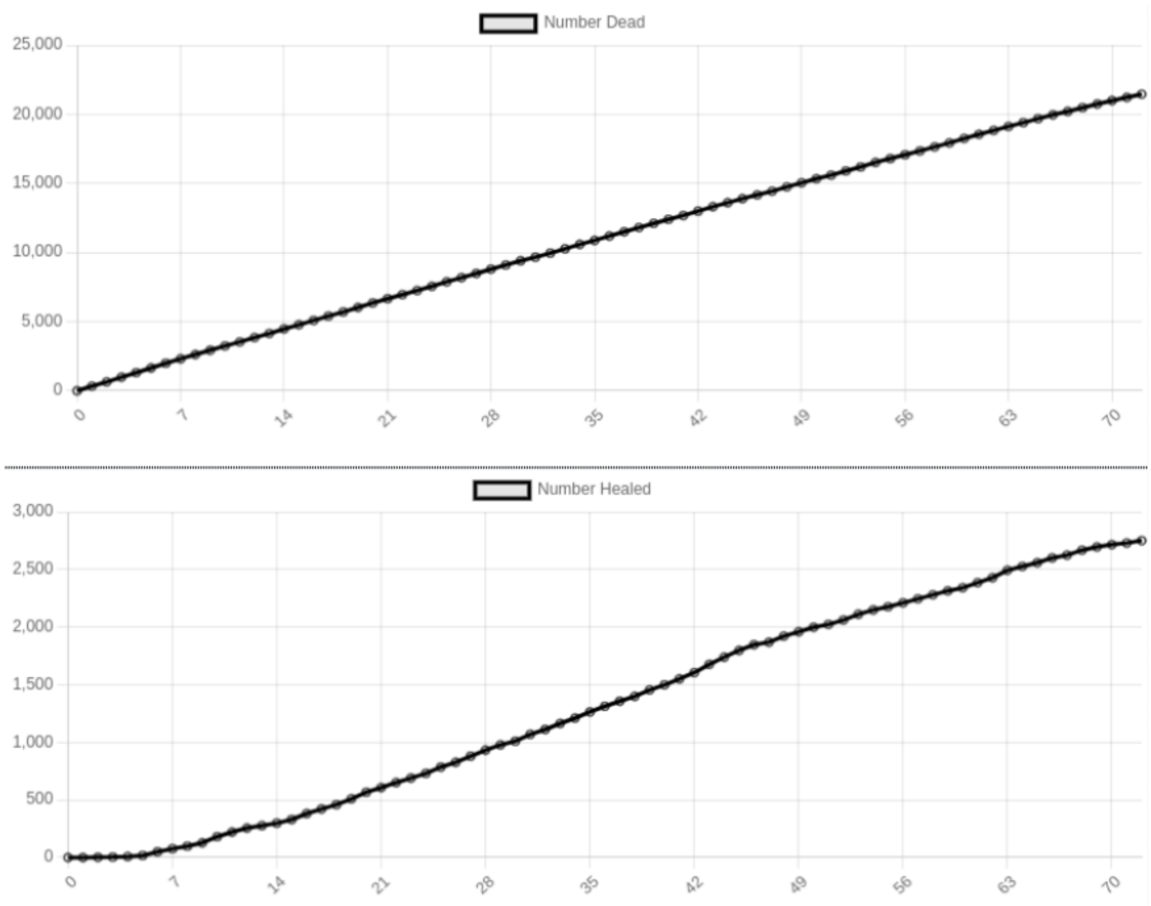

Figure 6.1: Number of dead and healed residents, with a timestep of five minutes per timestep

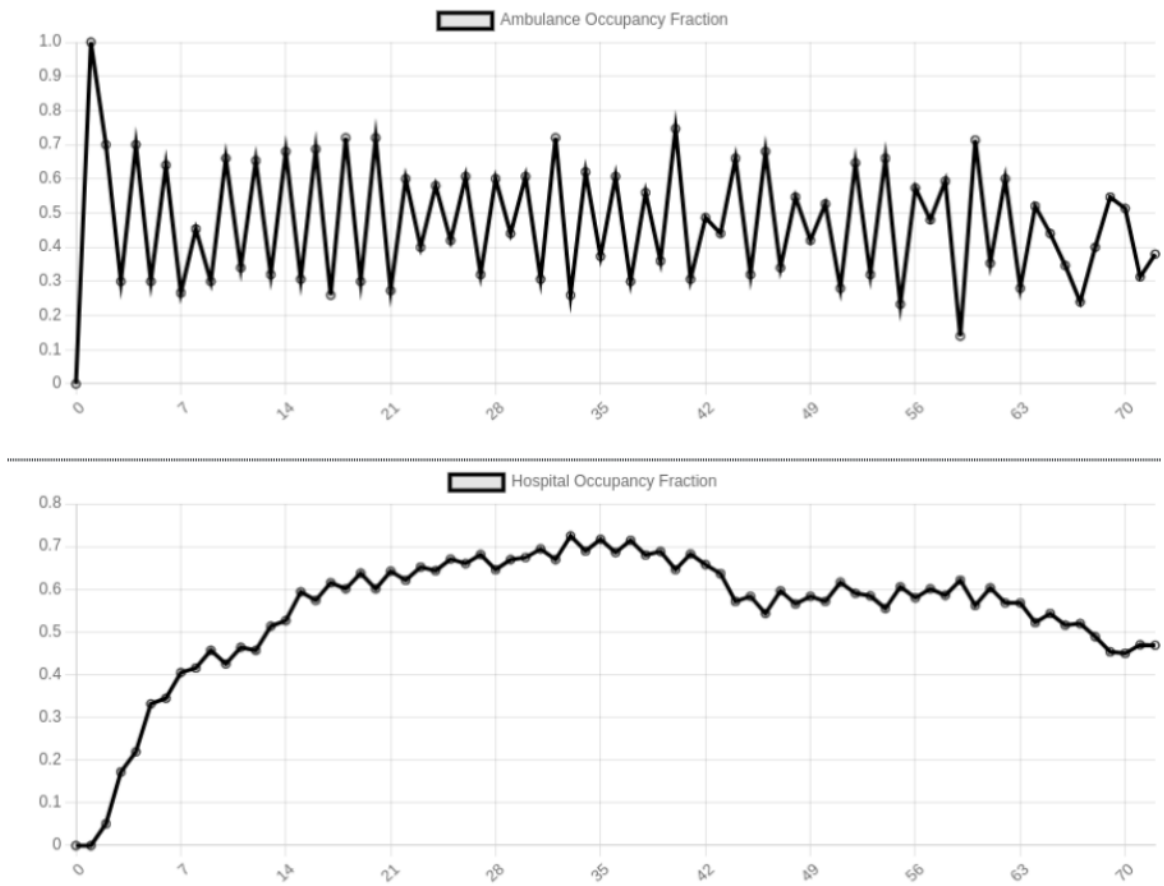

Figure 6.2: Ambulance and hospital occupancy fraction, with a timestep of five minutes per timestep

Appendix 6.2: Plots of implemented policy: Churches and schools are used as hospitals

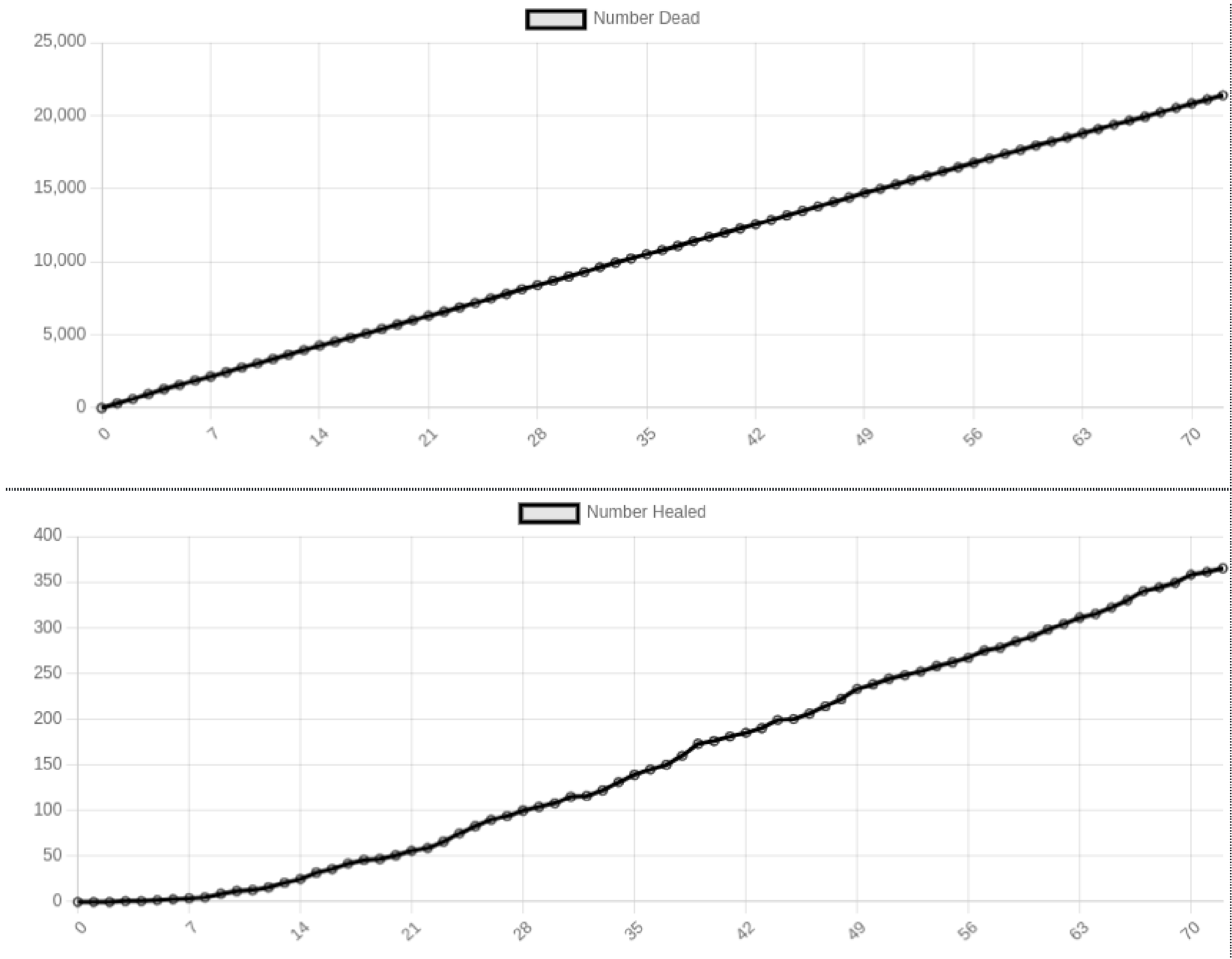

Figure 6.3: Number of dead and healed residents, with a timestep of five minutes per timestep

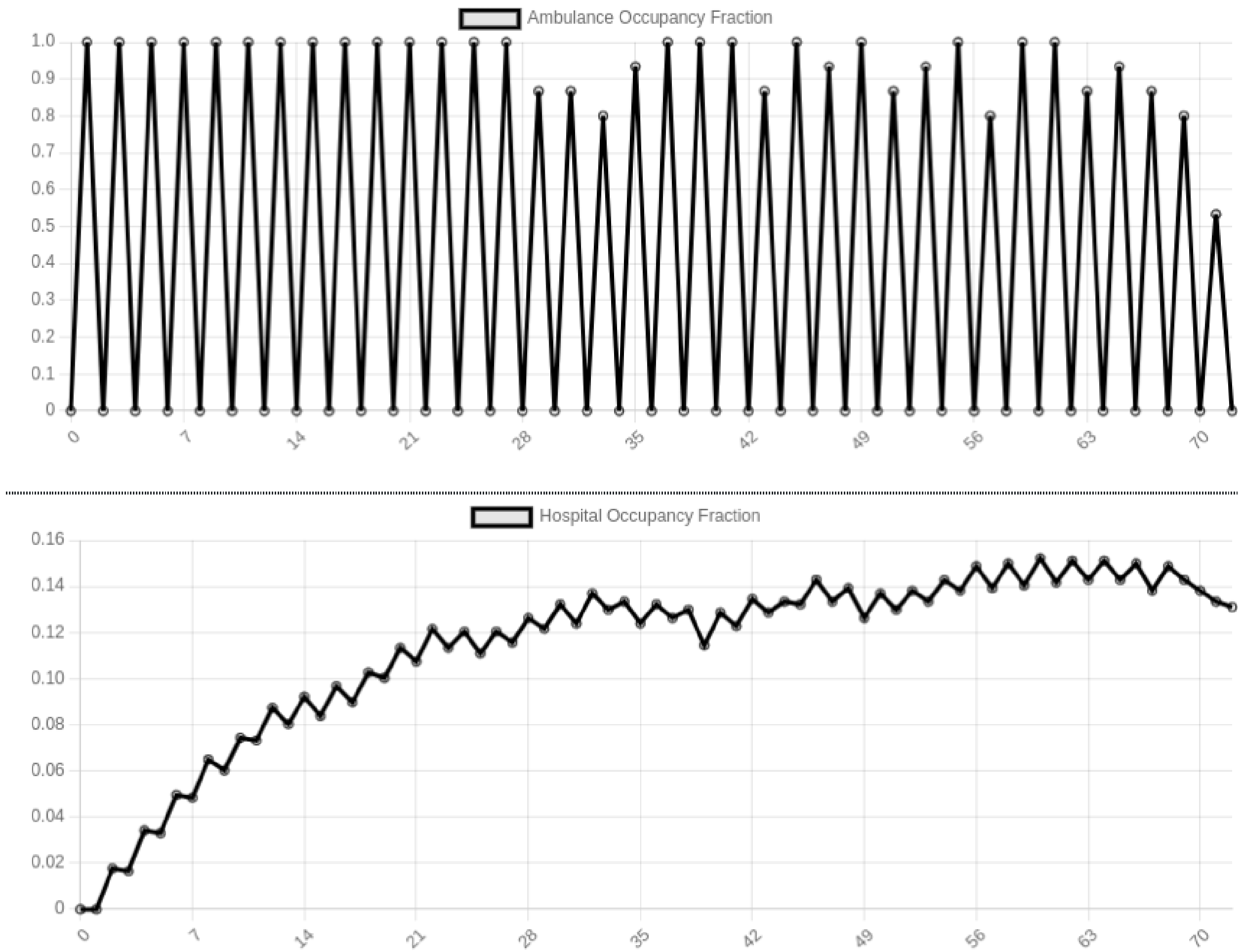

Figure 6.4: Ambulance and hospital occupancy fraction, with a timestep of five minutes per timestep

Appendix 6.3: Plots of implemented policy: First aid training for firefighters

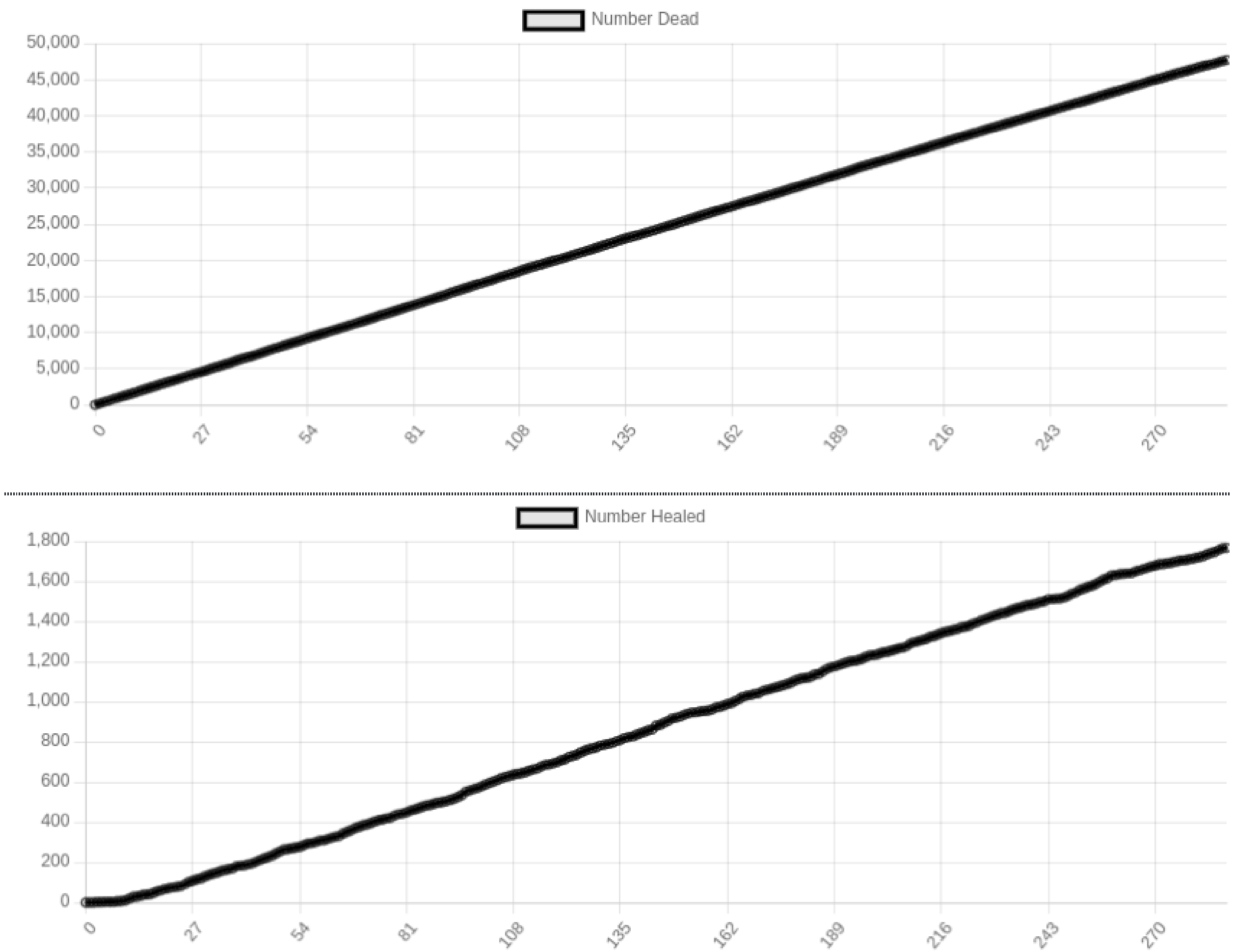

Figure 6.5: Number of dead and healed residents, with a timestep of five minutes per timestep

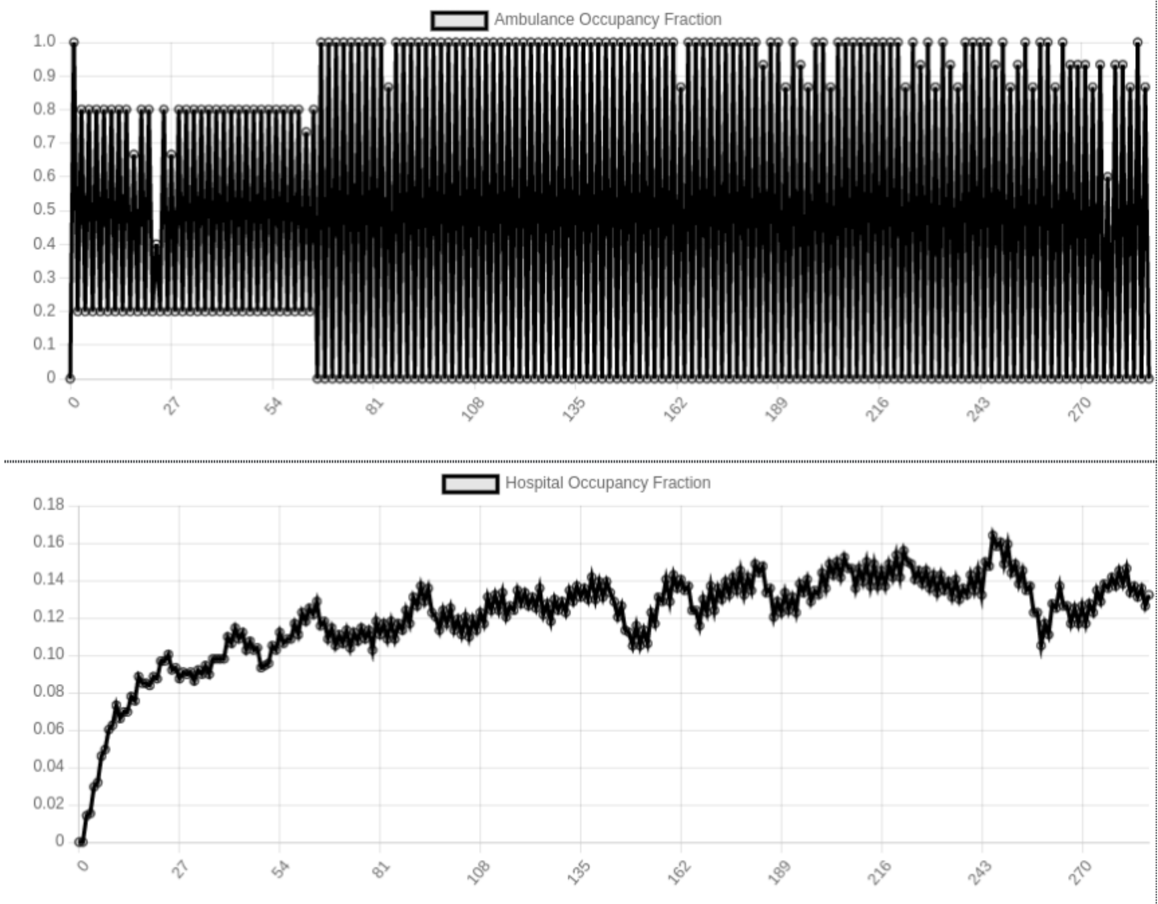

Figure 6.6: Ambulance and hospital occupancy fraction, with a timestep of five minutes per timestep