The effect of drone deployment on ambulance efficiency during an Earthquake

Using agent-based modelling to understand the effects drones can have during an earthquake in a western European city

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by

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Credits of the front page picture: [1].

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Preface

This research has been performed in the program of our Master at the faculty of Technology Policy and Management. The project is featured in the course SEN1211 Agent-Based Modelling.

Although we both already had some background in Agent-Based Modelling, this project lead to more insights into emergent behavior. It is fascinating that a small amount of simple rules for the agents and objects results in a working model that reflects the events in real-life.

We would like to thank Dr.Ir. Igor Nikolic and the TA's we contributed to this learning experience.

Contents

1 Introduction

Earthquakes are responsible for the third highest amount of fatalities due to natural hazards [2]. A country such as Italy always had many earthquakes, although it does not have the most severe earthquakes, it is still one of the countries which is most prone to earthquakes [3]. For instance, the 2009 earthquake in Abruzzi led to 300 deaths [4]. Most casualties are caused by building collapse. These collapsed buildings cause soft tissue injuries, fractures and crush injuries/syndrome which may lead to death [5]. Due to their high building density, densely populated areas face nearly the most severe consequences [6].

Unlike other natural disasters, earthquakes do not only cause casualties on impact, they also cause long-term damages [7]. Often patients require complex medical surgeries. However the hospitals that can perform these medical surgeries are often overloaded [7]. Therefore resources are needed to transport patients to hospitals. Because of this, earlier research has focused on developing organized, system-level response to an earthquake. Specifically aimed at directing ambulances to the correct hospital in the most efficient way. [8]. After an earthquake however, optimisation of routing proves to be very difficult [9].

Ambulances often face roadblocks which may makes it more difficult to pick-up patients and deliver them to the hospital [9]. Most roadblocks are caused by debris from damaged buildings, especially in narrow streets with a high building density. Furthermore older buildings tend to cause more road blocks [10]. GIS systems can be used to aid ambulance routing after a disaster. The data on blocked roads can be laid over the already existing network which can be used for ambulance routing [11].

There are several methods to gather the data on road blocks. First of all SAR (Syntethic Aperture Radar) can be used. SAR uses radio signals and can be used in all weather conditions [12]. Additionally LIDAR (Light Detection And Ranging) is the most accurate. but also most costly method to develop 3D-maps of the area. Last but not least, drones can be used to create digital pictures of the area [12]. Landscape maps made by processing the images of drones can be more accurate than from SAR data, although clouds deliver issues [13]. Another advantages of drones is that they tend to be low-cost. Furthermore small drones ranging from 1-5kg can fly for 20-60 minutes and sent and receive data inside radio-line-of-sight [14]. Furthermore these drones can be equipped with camera's ranging from smartphones to dedicated DSLR's [14].

This research will focus on the use of drones to aid ambulance routing. The drones will be used to investigate which roads are damaged. This data will be processed and used to decide which route ambulances should take.
Furthermore the densely populated city of Turin will be observed. Turin features a historic centre with many medium-sized apartments building in earthquake-prone Italy.
The main research question is therefore as follows:

What is the influence of drone observations for damaged road detection on the ambulance and hospital services in Turin under certain earthquake conditions as measures by the amount of deaths and recovered residents.

To answer this question, a model will be developed. The model will first be investigated on the behavior under different parameterizations and resemblance to real-life behavior. Furthermore the research question will be answered by a hypothesis. The hypothesis is as follows:

It is expected that a larger amount of drone observations for damaged road detection decreases the amount of deaths and increases the amount of recovered residents. Additionally a larger quantity and better quality, i.e. larger flying range, of drones is expected to result in more drone observations.

2
Method

2.1. Modelling Technique

For this research an Agent-Based Model will be built. Agent-Based Modelling is a technique to describe complex behavior: system level behavior that emerges from many simple interactions between entities within the system. All these smaller scale entities create interactions with other entities which leads to emergent behavior [15]. The model has been made in NetLogo, which is an free programmable modelling environment developed by the Northwestern University. [16]

2.2. Conceptualisation

The conceptualisation step provides a top-level view of what is being modelled. An overview will be given of what processes are modelled, what the model boundaries are, which agents are present in the model etc. 2.2.1 provides an overview of the whole system which is being modelled. 2.2.2 and **??** show the possible state and state changes for both the ambulances and drones. Last but not least 2.2.3 shows an overview of all the requirements.

2.2.1. System boundary and demarcation

Figure 2.1 shows the earthquake response system in Turin as a mindmap. On the left side all levers, external factors and key performance indicators (KPIs) can be found. The right side contains all agents and objects. Agents are entities in the system that 'think' and therefore have an complicated set of rules on which they act. Objects are entities which are mostly acted upon and in the case they act, they will only follow simple instructions.
The only agents in the system are ambulances and drones. Ambulances will drive to a patients location (destination) to pick the patient up. Furthermore the ambulance will bring the picked up patient to a hospital (destination). However, before picking up the patient, the ambulance will first check all residents in the building and perform minor help.
While the ambulance drives along the route to the destination, it will detect that some roads are available and some are blocked. Therefore the route will often change. Luckily, some other ambulances and drones also detect blocked roads. Therefore the ambulance will update his route according to the reroute frequency and take the knowledge of road availability into account.

Drones always start flying from a hospital. They will be targeted towards a nearby road of which the availability is yet unknown. The amount of of roads they can observe depends on their field of view, speed and flying range. Once the battery drops below a certain percentage of the flying range, they will return to their base hospital and start recharging.

The objects in the model are crossings, roads, residents and the earthquake. Only one building or one hospital can be placed at a crossing. Residents live in buildings and will be transported by ambulances to hospitals. Very slightly wounded residents can heal by themselves at home. Slightly wounded residents can heal if they are checked by an ambulance. Moderately wounded residents can heal inside an ambulance. Severely

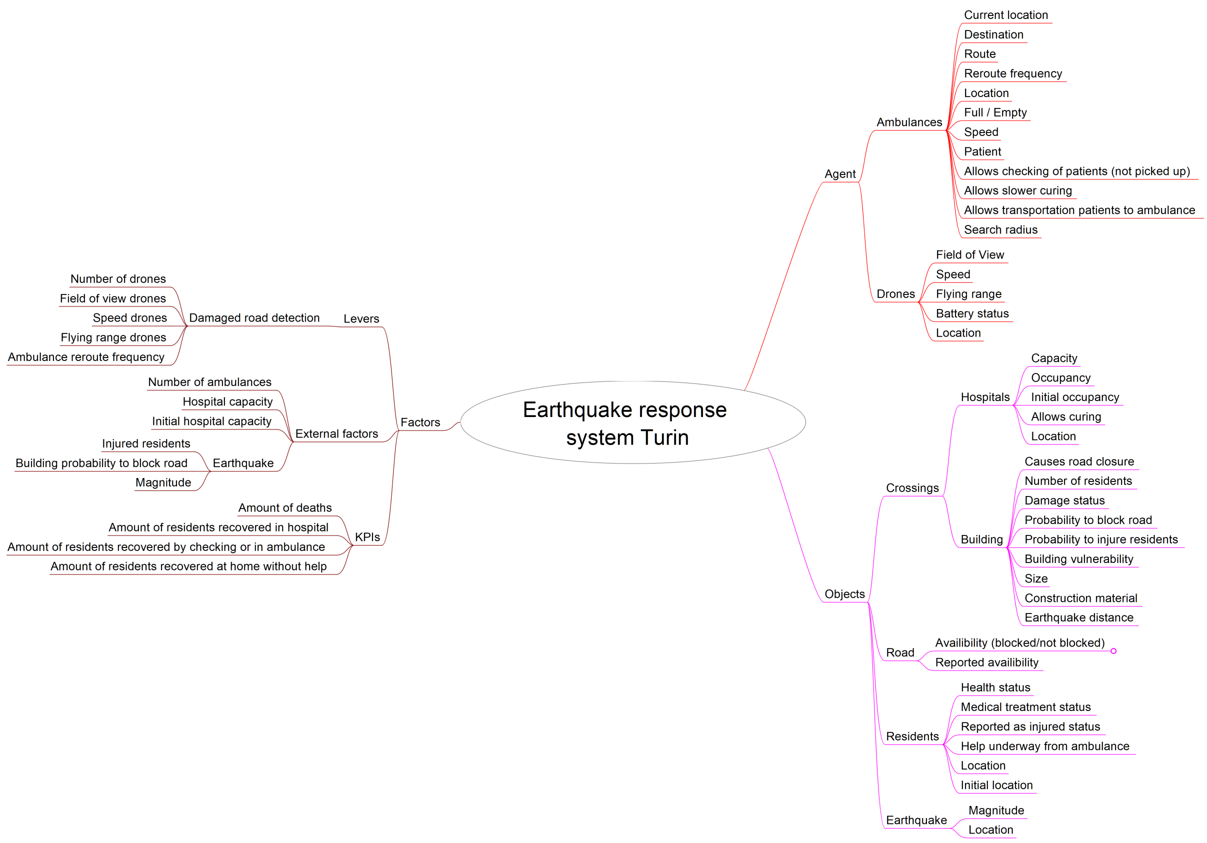

Figure 2.1: Mindmap of the Earthquake response sytem in Turin

wounded residents can only inside a hospital. If the resident is too heavily injured, it will not heal at all and will get increasingly more wounded. The injuries of a resident will worsen if they don't receive the medical treatment which belongs to their current injuries. There is only a single earthquake.

Last but not least, the model contains some factors. Levers are the input variables of which the impact on the KPI's should be measures in order to answer the main research question. External factors reflect the influence of the environment on the model itself.

2.2.2. Ambulances

Figure 2.2 shows the state diagram of the ambulances that are modelled. A state diagram shows how ambulances can change from one state into the next state.
At the start of the model ambulances will search for a patient. Once the ambulance has selected a patient in the neighborhood, it will be *On route to patient* and drive to the patient. It is important to note that ambulances can only select patients that have been reported as injured (called emergency).
While the ambulances are driving to the patient, they will regularly start rerouting. This means that they will construct the fastest route to the patient again. First of all this can happen because of the reroute frequency which means that the newest information on blocked roads will be used. Second this can happen if the ambulances accidentally faces a blocked road and a new route to the patient is still possible. The ambulance will report the road as not available and continue it's route. If the blocked road causes an *Unreachable patient*, a new target patient will be selected.
Once the ambulance arrived at the *residential building*, it will first check all the residents in the building and perform minor help. The ambulance will then pick up the most injured resident. This could be a different patient than the targeted patient if the targeted patient has died. If all residents in the building have died, the ambulance will search for a new patient and be *On route to patient* again.
If the ambulance has picked up the patient, it will select a hospital to drive to and be *On route to hospital*. The

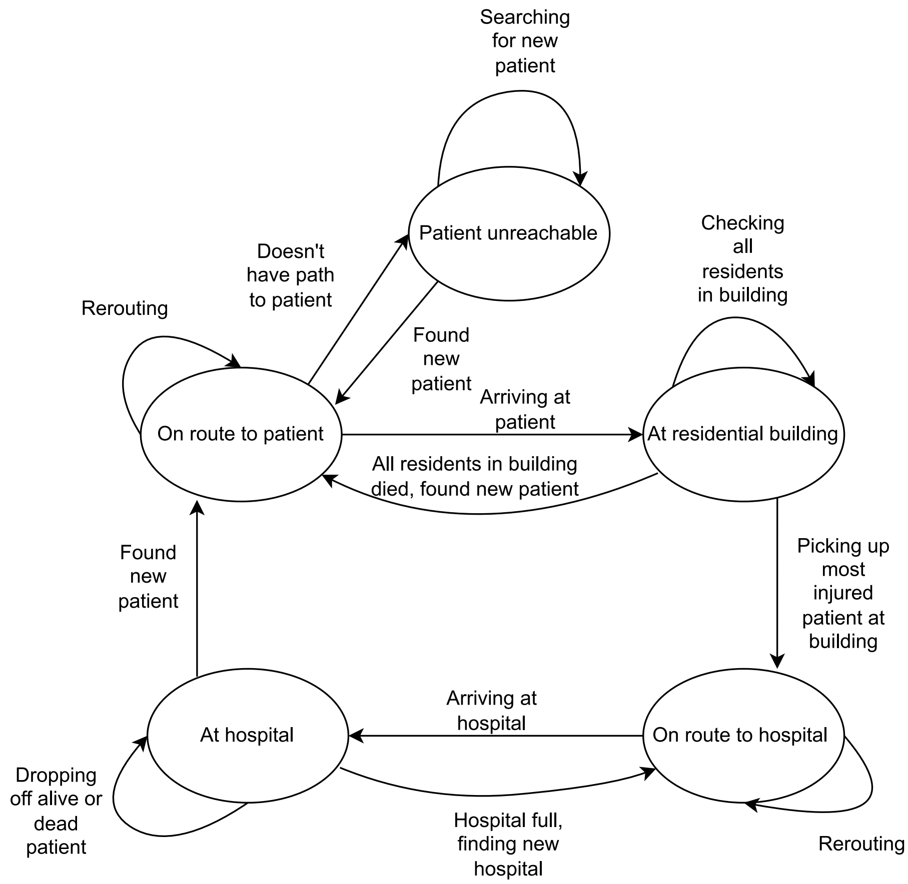

Figure 2.2: State Diagram Ambulances

ambulance will select the closes hospital which has a occupancy lower than the maximum capacity. Similarly to being on route to patient, the ambulance will be rerouting. Furthermore it is possible that the patient died in the ambulance if it is heavily injured. The ambulance will search for a new patient in that case.
Once *At hospital* there are two possibilities. If the hospital is full at arrival, the ambulance will drive to a new hospital. Otherwise the patient will be dropped of at the hospital. This will also happen if the patient died while dropping off at the hospital. After this has happened, a new patient will be searched for.

2.2.3. Requirements

A detailed requirements list has been made. This subsection will give an overview of the most essential requirements. A more detailed list can be found in 2.2.3

- A single tick represents 1 minute in real life
- All resources are in the city. No communication/ambulances from outside Turin.
- The simulation will run for 725 ticks (approximately 12 hours)
- Hospitals, buildings, roads, crossings and residents are objects
- Ambulances and drones are agents
- Every patch resembles 10 real-life meters
- Only a single earthquake event at the start of the simulation
- The earthquake can be created on any place inside or outside of the city (but within model).
- Only residents which are injured are created as object instances in the model. Uninjured are not.
- Residents can only be inside a building, ambulance or hospital. They can not be on the streets.
- Residents injuries are measured by a scale of 0-1. 1 is healthy, 0 is dead.
- Very slightly wounded residents can heal by themselves
- Slightly wounded residents can heal if checked by an ambulance
- Moderately wounded residents can heal inside an ambulance

- Severely wounded residents can heal inside a hospital
- Residents that are too heavily injured will only get increasingly more wounded and eventually die
- Healed residents arrange their own transport from the hospital to their house (and are removed from model)
- Residents are healed or increasingly wounded proportionally to their current health and medical treatment status
- Residents have to call 112 so the they are reported to the global state as injured.
- Building vulnerability depends on the building type (concrete/brick), building height, distance from epicenter multiplier and the earthquake intensity multiplier.
- Buildings have a certain number of residents.
- Roads can either be closed or open (binary).
- There is no other traffic on roads than the ambulances. There are no traffic jams.
- Ambulances transport injured residents. Residents are not moving to the hospital themselves.
- Ambulances have a speed of 1 road per tick independent of the length of the road.
- Ambulances have a capacity of 1 Drone flying time is affected by movement and hovering
- Drones have a range of 45 minutes flying time
- Once the battery has less than 50% capacity, the drone will fly to their base
- Once the battery has less than 50% capacity and a drones is at their base, the drone will charge
- Once a drones detects that a road is available/not available, it will report the status to the global state

2.3. Formalisation

This section will give an overview of how the conceptualisation develops into a model. A more clear view of the actual model will be shown. 2.3.1 describes how the map of Turin is implemented and the visualisation in the model. 2.3.2 shows all the global, object and agents variables and their range.

2.3.1. Map and visualisation

The map of Turin has been implemented by a Graphml file. This file contains all intersections as nodes and all roads as paths. Furthermore the length of the paths is proportional with the real-life length of the road. 2.3 and 2.4 show the map that has been implemented.

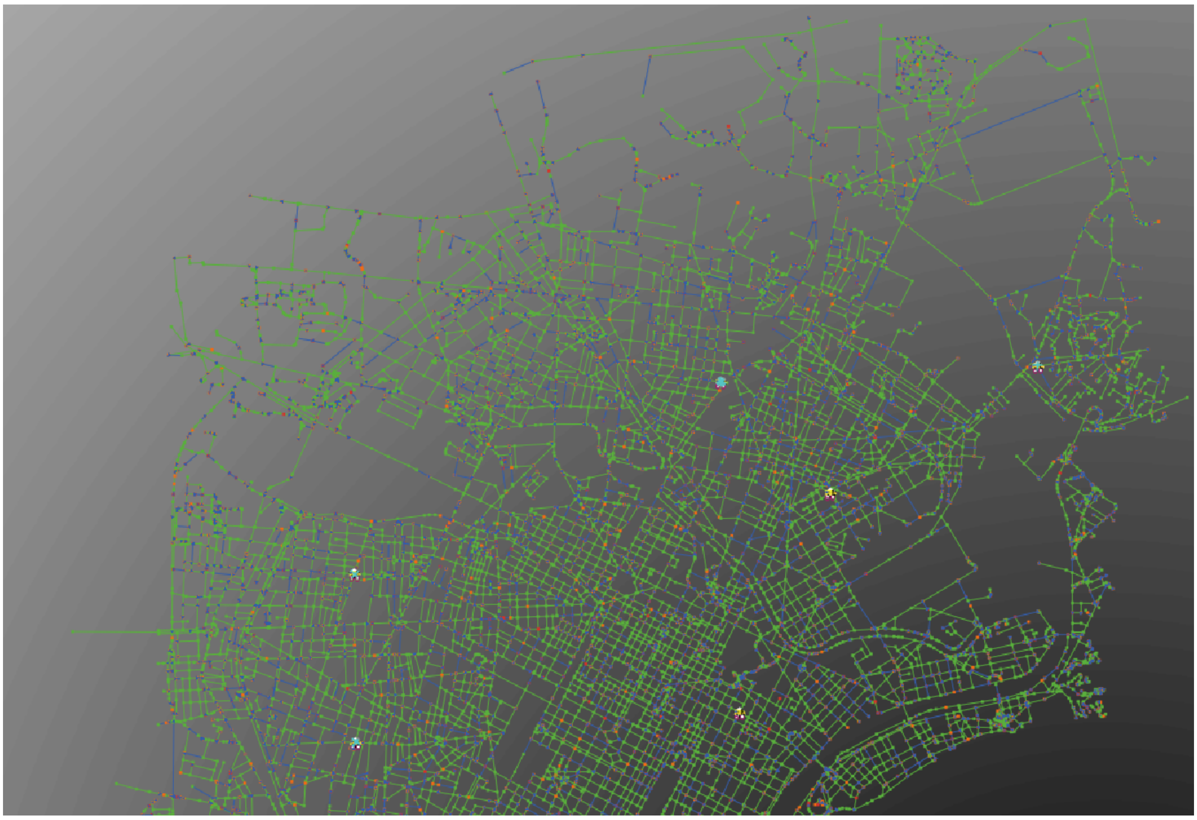

Figure 2.3: Map of Turin: north

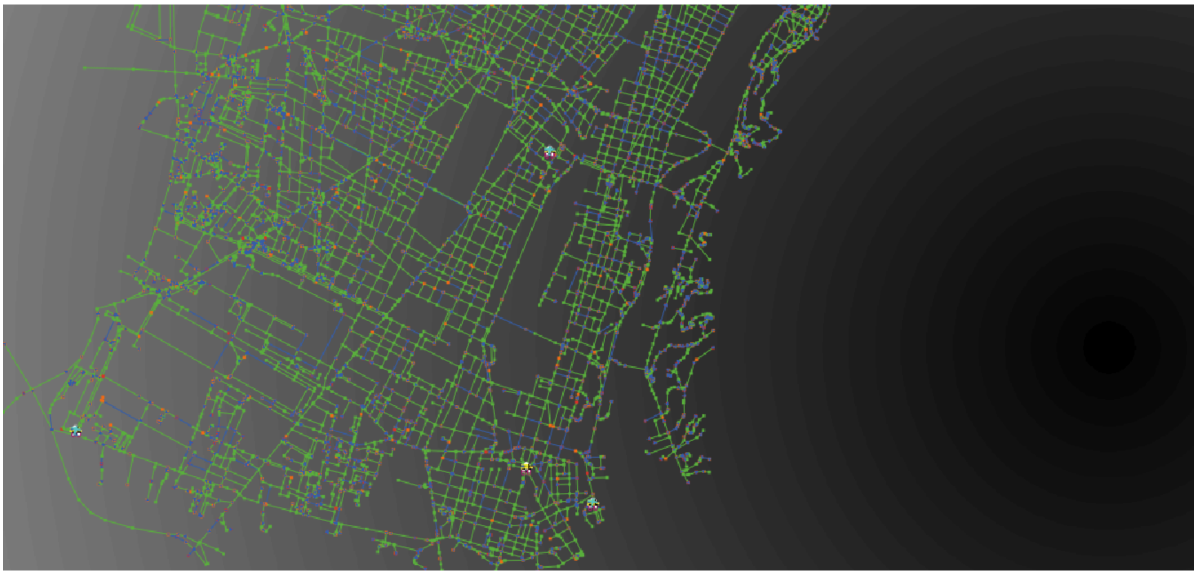

Figure 2.4: Map of Turin: south

2.5 shows a zoomed in version of the map. It can be seen that hospitals are represented as white houses. Furthermore hospitals have a larger size than buildings to improve the visibility. Furthermore ambulances are indicated as yellow ambulances. Drones are visualised by cyan airplanes. Residents are shown as blue arrows which are positioned on either buildings or hospitals. The direction the arrow is facing is not important in the model.

All buildings are represented depending on their damage status. Collapsed buildings can be seen as red circles, highly damaged buildings are orange circles and undamaged buildings are green.

Something similar takes place for the roads. Blocked roads can be either blue or red. Blue roads are blocked, but that is not reported to the global state. Therefore agents do not know that the road is blocked. Red roads are reported as blocked. Green roads are still available.

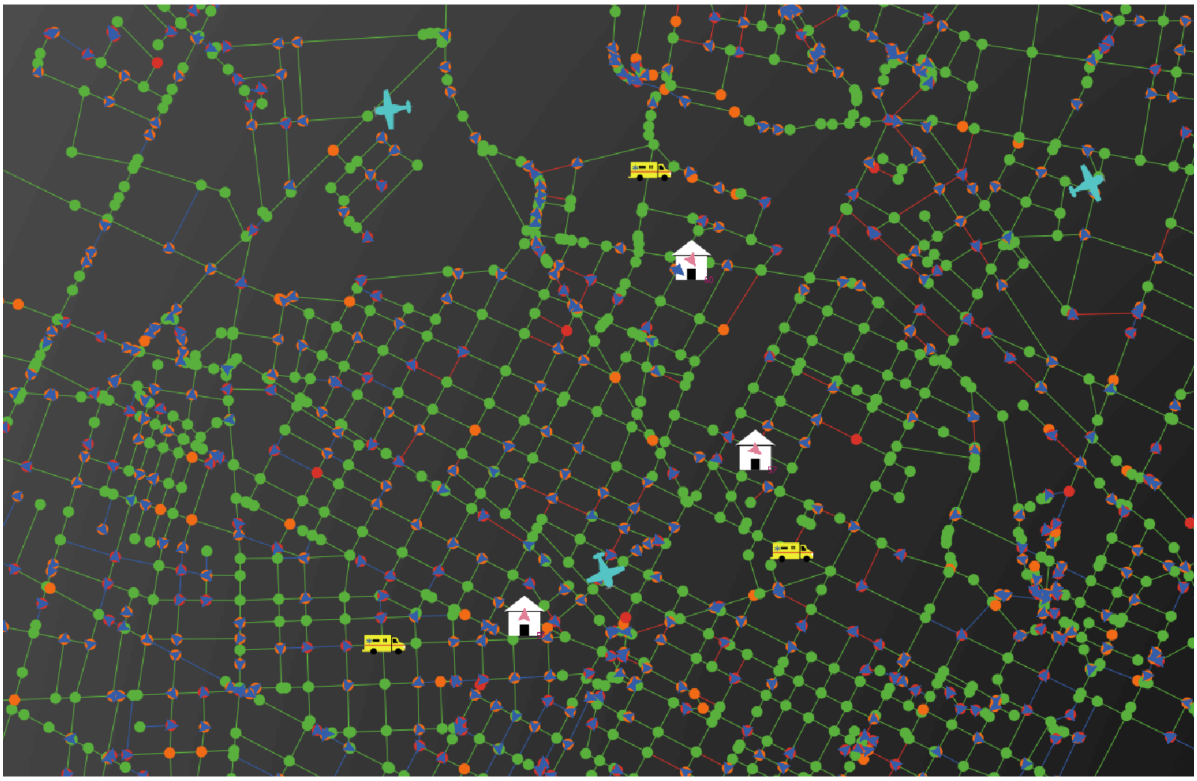

Figure 2.5: Zoomed in map

2.3.2. Variables

This section shows a list of all variables in the model. 2.6 shows all variables within the model with their ranges, desired values, units and some explanation. 2.7 displays a similar list for all the sliders in the model. Slider variables are variables that can be more easily adjusted compared to the variables within the model. Although both types of variables perform technically the same, the slider variables are more interesting for experimentation.

Entity	Variable	Range	Desired value	Unit	Other
Resident	Health	0-1	1 (Healthy)	x	
	Medical-treatment	"none", "checked","ambulance","hospital"	"hospital"	x	
	Reported?	False,True	True (injury reported to global state)	x	
	Help-underway?	False,True	True (Ambulance is incoming)	x	
	Calling?	False,True	True (Calling 112)	x	Only when call limit is in place
	Tries-calling?	False,True	True (Tries to call 112, could be rejected)	x	Only when call limit is in place
	Time-call	0-infinity	0 (short call)	Minutes	
Road	link_length	0-infinity	x	x	(ambulances move 1 road per tick, independent of length)
Buildings	Building-type	0.5-1	1 (concrete)	x	Buildings are called crossings in the model. Can only be 0.5 or 1
	Building-height	0.2-1	x	x	Can only be 0.2 (small), 0.6 (medium-height_ or 1.0 (tall)
	Earthquake distance	0-infinity	infinity	Amount of patches	In practice limited to size of the map
	Building-vulnerability	0-infinity	0	x	In practice limited to size of the map
	Building-status	"no-damage","collapsed","high-damage"	"no-damage"	x	
	Total-residents	1-20	x	Amount residents	
	Injured-residents	0	0	Amount injured residents	
	Spotted?	False,True	True (Spotted by drone)	x	
Hospitals	Capacity	0-infinity	infinity	Amount of patients	Initialised with 100
	Occupancy	0-infinity	0	Amount of patients	Initialised with 60%
Patches	Earthquake-center?	False,True	x	x	Did the earthquake happen on selected patch?
Ambulances	Destination	False,(crossing ... or hospital ...)	x	Crossing who number or hospital who number	
	Route	False, (Crossing ..., Crossing ... , etc. ie. Hospital ...	x	Crossing who number or hospital who number	List of crossings and/or hospitals on route
	Full?	False,True	x	x	Does the ambulance carry a patient
	Enroute?	False,True	x	x	Is the ambulance driving towards a patient or hospital
	Find-counter	0-5	0	ticks	For how many ticks didn't the ambulance find a patient when searching
Drones	Battery	0-100	[Maximum of Flying range]	Minutes of flying	Initialized the same values as Flying range
All turtles	Part-of-network?	False,True	x	x	Only True for buildings and hospitals, false for ambulances, residents etc.
Globals	Earthquake-location	[x,y]	x	Coordinates	Coordinates of patch with earthquake? True
	Min-earthquake-distance	0-infinity	x	Amount of patches	Resembles the distance from the closest crossing (from earthquake) to the earthquake
	Max-earthquake-distance	0-infinity	x	Amount of patches	Resembles the distance from the farthest crossing (from earthquake) to the earthquake
	Number-destroyed-streets	0- amount of roads	0	Amount of roads	Tracks how many roads are unavailable
	Number-destroyed-streets-spotted	0- amount of unavailable roads	Amount of unavailable roads	Amount of roads	Tracks how many roads that are unavailable are reported
	Fraction-destroyed-streets-spotted	0-1	1	x	Tracks how many roads that are unavailable are reported relatively
	Fraction-called-in	0-1	1	x	Tracks how many residents have reported their injury relatively.
	Deaths	0-infinity	0	Amount of residents	Tracks how many residents have died.
	Recovered-hospital	0-infinity	infinity	Amount of residents	Tracks how many residents have recovered inside a hospital
	Recovered-unchecked	0-infinity	infinity	Amount of residents	Tracks how many residents have recovered at home without checking of ambulance
	Recovered-with-help	0-infinity	infinity	Amount of residents	Tracks how many residents have recovered inside an ambulance or at home with checking

Figure 2.6: List of all variables and their ranges

Sliders	Earthquake-magnitude	0-1	0	x	
	Probability-call-112	0-100	100	%	Probability that resident ... calls 112 the current tick
	Amount-ambulances	0-infinity	infinity	Amount of ambulances	Limited to 250 in slider
	Amount-hospitals	0-infinity	infinity	Amount of hospitals	Limited to 30 in slider
	Hospital-capacity	0-infinity	infinity	Amount of patients	Limited to 250 in slider
	Hospital-filling-percegate-t0	0-100	0	%	Percentage of hospital capacity that was filled with patients before earthquake
	Initial-ambulance-search-radius	0-1900	x	Amount of patches	What is the radius in which the ambulance will initially search for a patient
	Percentage-concrete-buildings	0-100	100	%	
	High-damage-road-bloacked-chance	0-100	0	%	
	Collapsed-road-blocked-chance	0-100	0	%	
	Max-concurrent-calls	0-infinity	infinity	Amount of calls	Only works if call-limit is in place. Limited to 100 in slider
	Average-call-time	0-infinity	0	Minutes	Only works if call-limit is in place. Limited to 15 in slider
	Amount-drones	0-infinity	infinity	Amount of drones	Limited to 25 in slider
	Drone-speed	0-infinity	infinity	m/s	One patch is appr. 10 by 10 meters. Limited to 1 in slider
	Drone-view-radius	0-1900	1900	Amount of patches	Similarlyt to initial-ambulances-search-radius 1900 patchs is the max distance in model
	Drone-range	0-infinity	infinity	Minutes (1 tick is 1 minute)	Limited to 90 in slider
	Ambulance-reroute-frequency	0-infinity	0	Ticks	Ticks before rerouting of ambulance happens. Limited to 100 in slider

Figure 2.7: List of all slider variables and their ranges

3

Results

In this section results from model runs and experiments will be presented. First, a sensitivity analysis will be presented, in which the effect of each input variable on the KPIs is measured. Second, Finally, the model verification (including an extreme value test) and model validation will be shown.

Since this research is conducted using agent-based modelling, the focus will be on the dynamics and behaviour of the system, rather than quantified numbers. While the latter is the focus in a predictive model, this explanatory model is developed to increase understanding between the factors in the system and the complex or emergent behaviour.

3.1. Sensitivity analysis

Before policy packages are tested, this sensitivity analysis will provide insight in how much effect each of the input variables has on each of the KPIs. Each input variable is ran with -20% and +25% (divided by 1.25 and multiplied by 1.25), both with 25 replications. The results of those 16 * 2 * 25 = 800 runs are presented below.

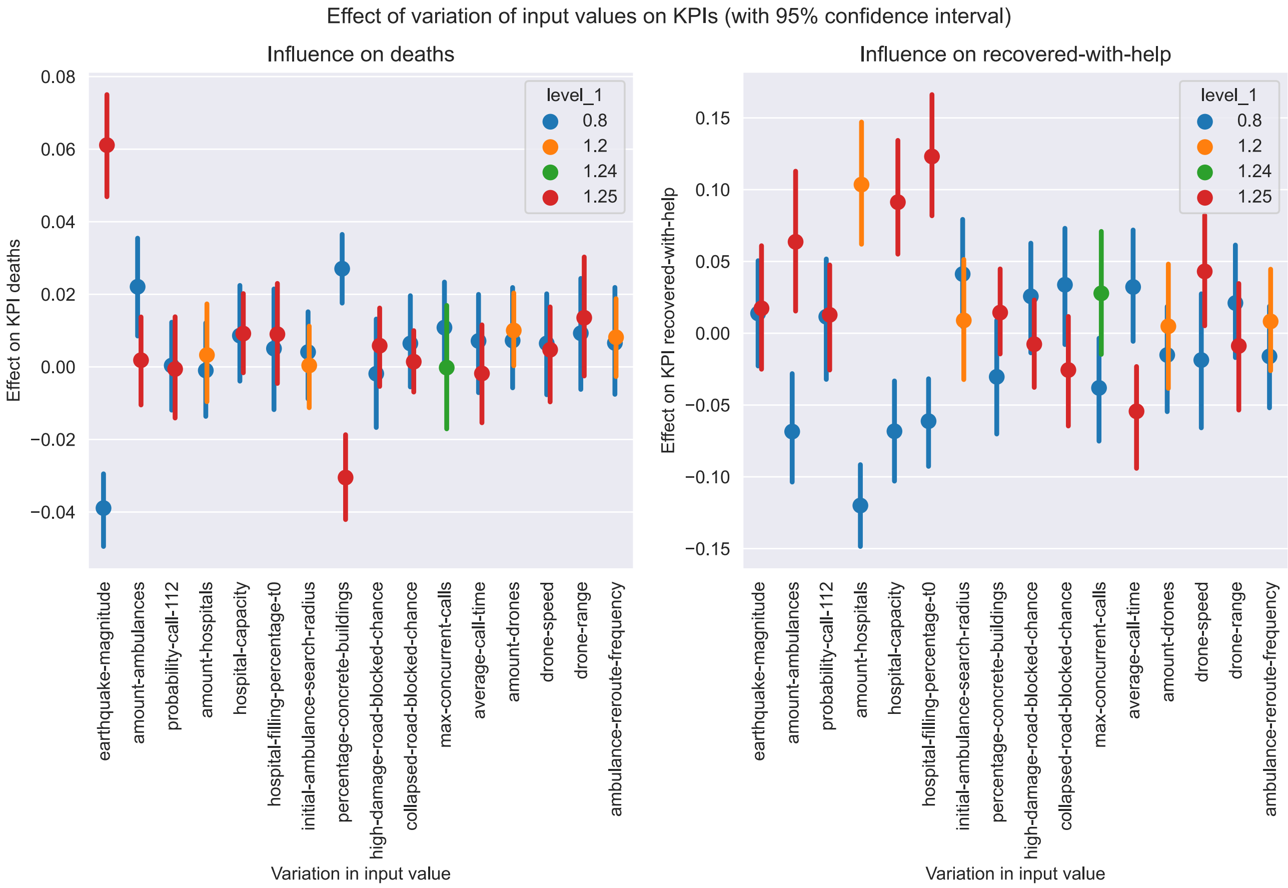

Figure 3.1: Relation between input values variation and KPIs

Looking at the first two KPIs, the earthquake magnitude and the percentage concrete buildings has a significant input on the number of deaths. An earthquake magnitude of +25% results in around 6% more deaths, while -20% results in 4% less deaths. A 20% less concrete buildings (so more brick) results in around 2.5% more deaths. The amount of ambulances also looks to have a impact, but is less significant.

More input variables have a significant influence of the recovered with ambulance help. A lower amount of hospitals has the highest negative influence (-12% with 8 instead of 10 hospitals). The amount of ambulances, hospital capacity and initial filling, and the average call time also have significant impact.

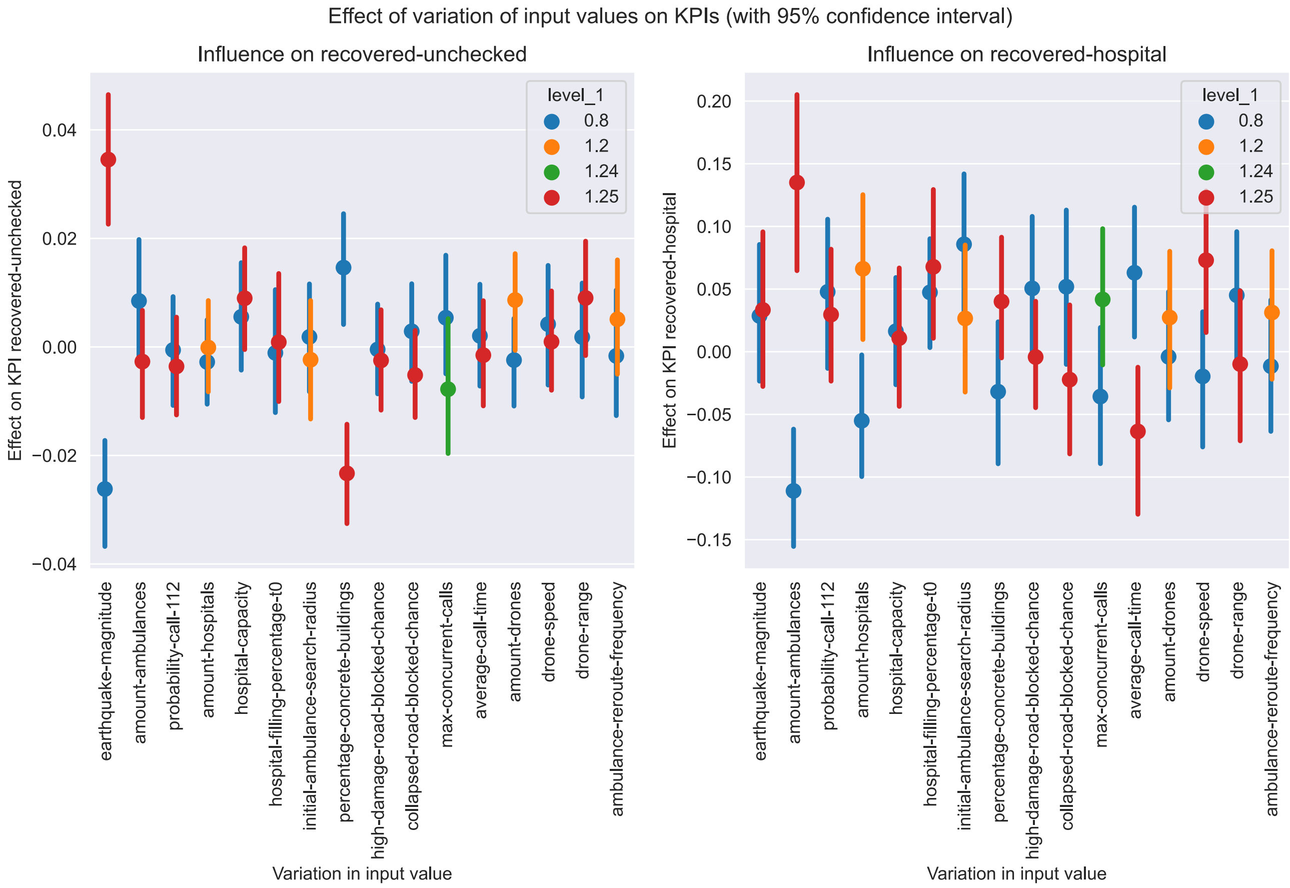

Figure 3.2: Relation between input values variation and KPIs

The second two KPIs, recovered-unchecked (without help) and recovered-hospital are also both significantly influenced by some KPIs. For recovered without help again the earthquake magnitude and the percentage concrete buildings has the most effect, as they did on the deaths KPI. For recovered in the hospital, most impact had the amount of hospitals, amount of ambulances and average call duration.

Notably, the drone variables have not very large impacts on the KPIs. In the policy experiments this will be discussed further.

Ideally, the interaction effects of varying multiple input values are also measured. However, due to the long run time, high randomness (and thus high variability) and many input variables this is not feasible for this project.

With the policies combinations of input variables are varried, to give some insight in combinations of different drones.

3.2. Policy results

3.2.1. Experimental setup

Seven policy packages were tested in the ABM, with the specific lever (input variable) values listed in table 3.1.

Policy package	amount-drones	drone-view-radius	drone-range	ambulance-reroute-frequency
0_no-drones	0	25	30	10
1_short-range	10	25	30	10
2_slow-reroute	10	25	45	10
3_more-drones	20	25	45	10
4_large-view	20	50	45	10
5_fast-reroute	20	50	45	5
6_many-long-range	40	50	60	5

Table 3.1: Experimental setup, showing the input values for each policy package

Each of the policy packages was run 25 times, since the initialization of the model has a high degree of randomness. Especially the random placement of the hospitals matters a lot. If one area has no hospital, or two hospitals are placed close together, this most likely will make hospitals less effective.

A (list of) random seed(s) was purposely not used, to keep the model variation included, and don't show correlations that only occur in specific circumstances.

3.2.2. Static results

First, the effects of the different policies on the KPIs values in the last timestep (tick 720 or 12 hours) in figure 3.3.

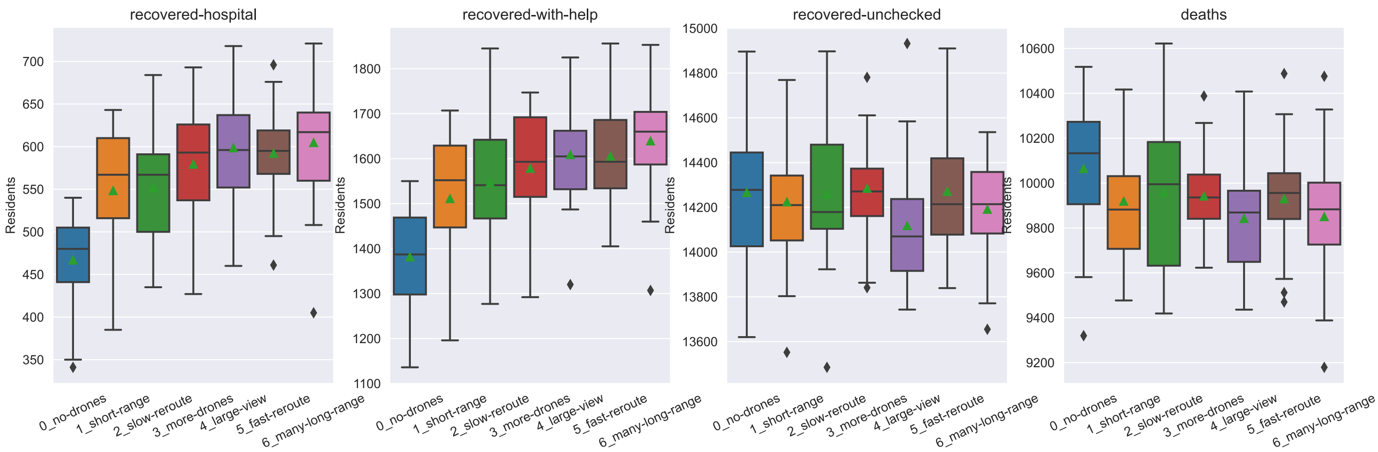

Figure 3.3: Boxplots of recovered residents at the end of the simulation

The boxplots show that there is a clear increase in median and mean (green triangle) values for recovered in the hospital and recovered with help from the ambulances KPIs, when using drones compared to not using them. An upward trend in those KPIs can be seen as more and more capable drones are used, but with diminishing returns. However, the statistical variation for each policy is still quite large, so this should be further investigated with more compute time allowing for more model runs to determine if those scenarios difference are actually statistical significant.

For the two other KPIs, the residents recovered without help and residents died, no trend or significant correlation is present. It looks like the number of deaths is slightly (also see our model limitations).

3.2.3. Dynamics

The dynamics of the model shown in figure 3.4.

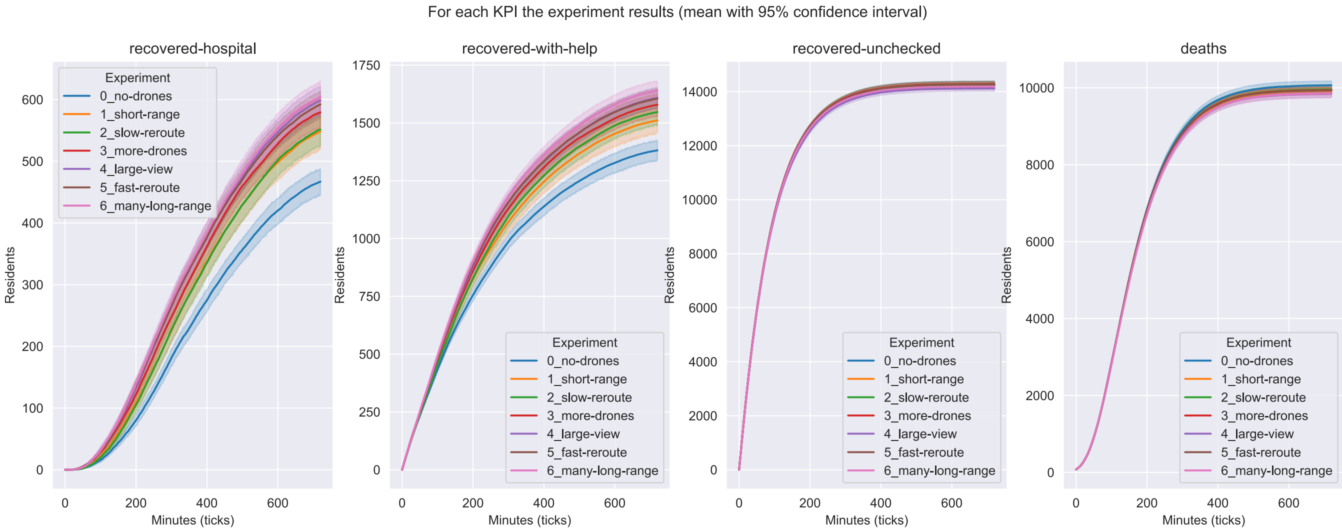

Figure 3.4: Lineplot of recovered residents during the simulation

The development of the KPI values during the model run is largely consistent with the static results presented in boxplot 3.3. The no drones policy clearly shows a lower number of residents recovered in the hospital or recovered with ambulance help, while recovered without help and deaths are insignificant. Between the drones policies the former KPIs show no clear relation, but the pol
Finally, in figure 3.5, a more direct metric can be seen, the fraction of the streets that are spotted (either by ambulance or drone).

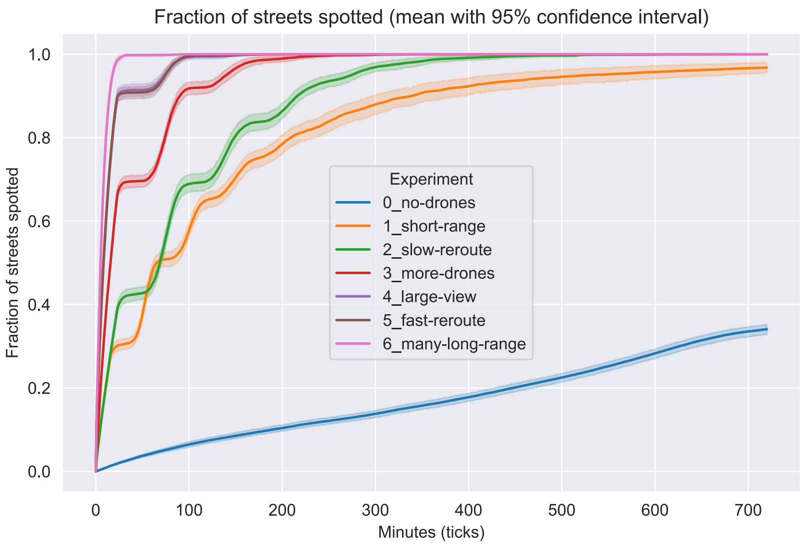

Figure 3.5: Lineplot of recovered residents during the simulation

In the policy without drones, less than 40% of the destroyed streets are spotted by ambulances after the 12 hours. This means they will continue to no know which residents are reachable by road and continue to encounter blocked road segments, and having to do a costly reroute.
Even with only 10 small, short-range drones in policy 1, this number more than double to over 90% of roads spotted. Starting from policy 2 with the regular-range drones, almost all roads get spotted in each model run towards the end of the model, often within 8 hours. With policy 3 with double the drones this happens after approximately 4 hours, for policy 5 in 2 hours, and in the policy 6 with the most and most capable drones comfortably within a single hour.

This supports the results from our more high-level KPIs presented earlier, since each drone scenario actually provides a better view of the network, making more efficient routes possible and ensuring ambulances don't try to find a route to residents that are unreachable.
Notable is that the faction of streets spotted is not increasing in a fluent curve, but with steps. This is the results of drones all starting with a full charge, all deploying immediately, and all needing to recharge after the same time. It could be interesting to investigate other release patterns in future research.

3.3. Verification

This section will show whether the model has been implemented correctly from the conceptualisation. While modelling, sufficient small tests have been informed. Such as checking whether the building vulnerability was correctly calculated.
3.6 shows the results of the extreme value tests. The extreme value tests was performed by varying input variables with larger amounts such as +80% or -80%. It shows whether the model still produces reasonable results, even if there is a significant amount of unexpected behaviour.

As we can see, the extreme value test shows more or less linear results. The residents that have recovered unchecked (at home without help) or resident that have died barely change while varying the amount of ambulances or hospitals. These KPI's also show a more or less linear line while varying the earthquake magnitude. It should be noticed that the results while varying the earthquake magnitude barely differ when taking the scale into account. An earthquake which is 80% less strong, only results in 15% less deaths.
The amount of recovered residents inside a hospital or recovered by help, which means that the resident recovered due to checking by an ambulance or recovered inside an ambulance, show linear proportional behavior while varying the amount of ambulances or amount of hospitals. It should be noted that the amount of recovered residents inside a hospital increases less steep when having more hospitals that it decreases by having less hospitals. Furthermore these KPI's show more or less linear proportional behavior while varying the earthquake magnitude, even if the differences are small.

Therefore it can be concluded that the model still produces reasonable results when facing unexpected behavior. The model is fit for purpose even when more extreme conditions are applied.

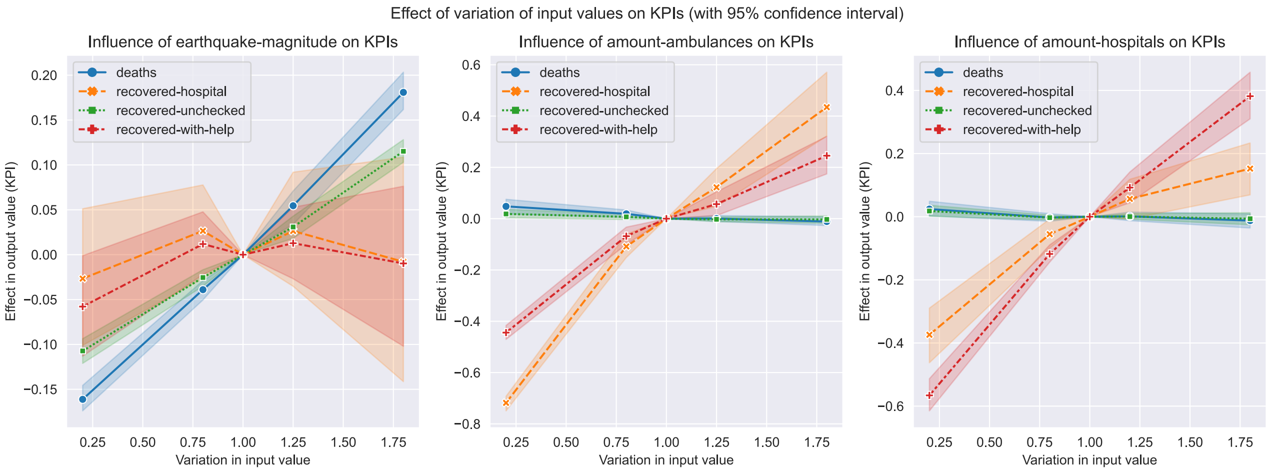

Figure 3.6: Relation between (extreme) input values variation and KPIs

3.4. Validation

The validation tests will check whether the behavior that derives from the model is comparable to real-life behavior. The validation will mostly focus on the amount of deaths and the amount of roads blocked in the city because these two functions are the main functions of the model.
According to [17] a 6.2 magnitude earthquake in Italy has killed 290 people. Furthermore the heavy earthquake in L'Aquila with a 6.3 magnitude earthquake has killed 308 people [17]. The 7 magnitude Haiti earthquake has killed around 230,000 people in 2010 [18]. Last but not least, 3774 disaster-related deaths have

been reported due to the 9.0 earthquake 2011 in Japan [19]. However this last number also includes deaths due to suicide and respiratory diseases which appeared later than the earthquake itself.

The results in the boxplots of figure 3.3 show that our model generates between approximately 9400 and 10600 deaths. This is significantly higher than the amount of deaths in mentioned earthquakes in Japan and Italy. Although the amount of deaths in Haiti was significantly higher, the situation in Turin can not be fully compared with Haiti. Turin is a more developed city with houses featuring a higher construction quality. Furthermore the governance in Italy is of a significantly higher quality. Therefore it is thought that the model produces an amount of deaths which is too high. An inherently amount of deaths generated by the model is therefore a model limitation.

Our base scenario shows that about 13% of road are damaged with the default model settings. Research shows that 84% of the roads in Christchurch were not damaged at all after the 2010 7.1 magnitude earthquake in Darfield and the 2011 6.2 magnitude earthquake in Christchurch itself [20]. Furthermore the road network in L'Aquila did not have significant damages besides a viaduct and bride. However falling debris and landslides after the earthquake and the heavy rainfall degraded the functionality of the road network [20].

4

Conclusion & discussion

This research has started with the following main research question: *What is the influence of drone observations for damaged road detection on the ambulance and hospital services in Turin under certain earthquake conditions as measures by the amount of deaths and recovered residents.*
The results show that there is a significant difference between the policies without drones and the policies with drones. Therefore it can be concluded that there is a significant influence of drone observations on the amount of recovered residents. Furthermore there is a smaller difference between amount and capability of drones. Only the scenario with short range drones shows worse results, although still far better results than the scenario without drones.

Therefore it is recommended for emergency services in earthquake-areas to include a small fleet of drones. The results show that even simple drones with a short range can give large benefits. Furthermore these drones can be used for other emergencies besides earthquakes.

The model itself features many limitations. For instance the amount of deaths in the model is too high compared to previous heavy earthquakes. This is mainly caused by a skewed health initialization and degradation, in the real world more residents would heal on their own or degrade less fast. Therefore new research could focus on a model without this limitation.

Furthermore this research did not take a few factors into account. For instance the model lacks a traffic system which includes traffic jams. It could be researched what happens if residents are on the streets and cause traffic jams for ambulances.
It's also assumed that an ambulance can check every resident in a building without that taking extra time. It would be more likely that an ambulance can only thread one or two patients at the same time, so taking care of other residents in a building would take extra time.
Furthermore the model assumes that every patient will be transported to the hospital by an ambulance. However this might not be the case in a real earthquake. It could be investigated whether people try to get to the hospitals themselves and what problems derive from that.
Future research could also test the influence of other assumptions on the operations of emergency services. For instance, drones spot the availability of the roads in their Field of view correctly. But what happens if some data is incorrect?

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5

Appendix A: Requirements

The following tables show a list of all requirements.

		Requirement	Description
OBJ	RE	1	Only residents which are injured are created as object instances in the model. Uninjured are not.
OBJ	RE	2	Residents can only be inside a building, ambulance or hospital. They can not be on the streets.
OBJ	RE	3	Residents injuries are measured by a scale of 0-1. 1 is healthy, 0 is dead.
OBJ	RE	4	Residents die when their health drops to or below 0 (and are removed from the model)
OBJ	RE	15	Healed residents arrange their own transport from the hospital to their house (and are removed from model)
OBJ	RE	22	Residents are healed or increasingly wounded proportionally to their current health and medical treatment status
OBJ	RE	23	Very slightly wounded residents can heal by themselves
OBJ	RE	24	Slightly wounded residents can heal if checked by an ambulance
OBJ	RE	25	Moderately wounded residents can heal inside an ambulance
OBJ	RE	26	Severely wounded residents can heal inside a hospital
OBJ	RE	27	Residents that are too heavily injured will only get increasingly more wounded and eventually die
OBJ	RE	28	With a call limit, the call-time depends on a random poisson distribution for the resident in the building that is calling
OBJ	RE	29	Without a call limit, the probability that 112 is called from a building depends from a random distribution and the amount of resident in the building
OBJ	RE	30	Both with or without a call limit, only a single resident to call 112 for the rest of the residents.
OBJ	RE	31	Both with or without a call limit, Slightly injured and heavily severely residents have the same probability to call 112
OBJ	RE	32	Residents have to call 112 so the they are reported to the global state as injured.
OBJ	RE	33	The health of residents in a collapsed building are initialized according to normal distribution with average 0.8 and standard deviation 0.3
OBJ	RE	34	The health of residents in a high-damage building are initialized according to normal distribution with average 0.95 and standard deviation 0.3
OBJ	BU	1	Building vulnerability depends on the building type (concrete/brick), building height, distance from epicenter multiplier and the earthquake intensity multiplier.
OBJ	BU	2	Building collapse probability, high damage probability and no damage probability are randomly sampled by a multinomial distribution depending on the building vulnerability
OBJ	BU	3	Buildings have a certain number of residents.
OBJ	BU	4	Building type and resident distributions are uniform through the whole city
OBJ	BU	5	Building types and sizes are not correlated
OBJ	BU	6	The only possible values for building-type are 1 and 0.5.
OBJ	BU	7	The only possible values for building-height are 1 (tall), 0.6 (medium and 0.2 (small).
OBJ	BU	8	Building types and heights are uniformly distributed over the city
OBJ	BU	9	The building type is determined by a random distribution which depends on a slider. The slider says how much percent of the buildings is from concrete.
OBJ	BU	10	The amount of residents in each building depends on the height of the building and some random distribution
OBJ	BU	11	Tall buildings have between 10 and 20 residents.
OBJ	BU	12	Medium sized building have between 5 and 10 residents.
OBJ	BU	13	Small building have between 1 and 5 residents.
OBJ	BU	14	The farthest building from the earthquake epicenter has a vulnerability of 0 due to the Building Vulnerability formula.
OBJ	BU	15	10% Of buildings are tall, 30% medium-height and 60% small

OBJ	RO	1	Roads can either be closed or open (binary).
OBJ	RO	2	Roads are undirected
OBJ	RO	3	There is no other traffic on roads than the ambulances. There are no traffic jams.
OBJ	RO	4	Crossings are always open.
OBJ	RO	5	Either a hosptial or a building can be put on to a crossing.
OBJ	RO	6	When a crossing is chosen to be a hospital, the breed of the crossing changes to 'hospitals'.
OBJ	RO	7	Every crossing has either 1 building or 1 hospital.
OBJ	RO	8	Roads will not be repaired.
OBJ	HP	1	Hospitals have a certain capacity
OBJ	HP	2	During initialization, hospitals are filled with a certain amount of patients (belonging to residents class).
OBJ	HP	3	The amount of initial patients is determined by a percentage of the capacity of the hospital. This percentage is determined by a slider from 0 to 100%
OBJ	HP	4	Hospitals have a capacity of 100
OBJ	HP	5	The amount of hospitals in the model depends on a slider ranging from 1 to 30
OBJ	HP	7	Hospitals have the color white and size 12.
OBJ	HP	8	Hospitals randomly hatched over crossings with at least 3 link-neighbors (connected to >= roads)

		Requirement	Description
AGT	AM	2	Ambulances transport injured residents. Residents are not moving to the hospital themselves.
AGT	AM	4	During initialization, ambulances are set to be empty (not have a patient)
AGT	AM	6	Ambulances have a speed of 1 road per tick independent of the length of the road.
AGT	AM	7	Ambulances have a capacity of 1
AGT	AM	8	Ambulances dron't drive over roads in the model. They move from crossing to crossing
AGT	AM	9	Once ambulances face an closed road, they will try to find another route based on current knowledge in the global state
AGT	AM	11	Ambulance will check whether a road is open or closed at the start of the tick and drive through them during the tick.
AGT	AM	12	At the start of a trip ambulance will construct a route based on the knowledge of open/closed roads.
AGT	AM	13	During a trip, ambulances will check every 5 ticks whether their current route is still valid, based on the information in the global state
AGT	AM	15	If a patient dies when being transported in an ambulance, the ambulance will still deliver the body to the hospital.
AGT	AM	16	Once ambulances face an closed road, they will report to global state that the road is closed
AGT	AM	17	Ambulance takes the most injured resident from a building
AGT	AM	18	During initialization, ambulances are placed randomly over the hospitals
AGT	AM	19	When ambulances search for patients in their neighborhood, they will first search for the most heavily injured residents in a radius of 5 distance over the roads
AGT	AM	20	When ambulancse can find a patient in the radius of 5, they will continuously increase the radius by factor 1.5
AGT	AM	21	The ambulance will die when there have been more than 100 ticks, and an ambulance can't find a new patient for 5 ticks
AGT	AM	22	Ambulances will die if there are no more residents in the model that are not already treated by the hospital.
AGT	AM	23	Once Ambulances arrive at a building, they will first check every resident and perform minor help. After that they will pick up their patient
AGT	AM	24	There are 40 Ambulances
AGT	AM	25	Ambulances wil search for a new patient if they can't reach their selected patient
AGT	AM	26	When the ambulances have picked up a patient, they will drive to the closest hospital that has a occupancy lower than the capacity.
AGT	AM	27	If the hospital is full when the ambulances arrives, it will select and drive to another hospital
OBJ	DR	1	Drone flying time is affected by movement and hovering
OBJ	DR	2	Drones have a 360 degree view with certain range
OBJ	DR	5	Drones share knowledge automatically to the global state
OBJ	DR	6	There are 10 drones
OBJ	DR	7	During initialization, drones are placed randomly over the hospitals
OBJ	DR	8	The drone has the initial hospital as a base
OBJ	DR	9	Drones have a range of 45 minutes flying time
OBJ	DR	10	Once the battery has less than 50% capacity, the drone will fly to their base
OBJ	DR	11	Once the battery has less than 50% capacity and a drones is at their base, the drone will charge
OBJ	DR	12	Drones will keep charging until 100% battery capacity and then start flying
OBJ	DR	13	Drones will fly to the closed crossing of which the roads have not been reported as available/not available according to the global state
OBJ	DR	14	Once a drones detects that a road is available/not available, it will report the status to the global state
OBJ	DR	15	Drones have a viewing radius of 250 meters (actual radius not relative to road distance)
OBJ	DR	16	Drones have a speed of approximately 5 m/s
OBJ	DR	17	Drones fly over the patches, not over the roads
OBJ	DR	18	Drones start with a 100% full battery

		Requirement	Description
MOD	MN	3	All resources are in the city. No communication/ambulances from outside Turin.
MOD	MN	4	A single tick represents 1 minute in real life.
MOD	MN	5	The simulation will run for 725 ticks (approximately 12 hours)
MOD	MN	6	The amount of total residents, injured uninjured and healed, are saved in the model
MOD	MN	7	Hospitals are placed over the crossings at first. After that buildings are placed.
MOD	MN	8	Hospitals, buildings, roads, crossings, residents are objects
MOD	MN	9	Ambulances and drones are agents
MOD	MN	10	Every patch resembles 10 real-life meters
MOD	EQ	1	Only a single earthquake event at the start of the simulation
MOD	EQ	2	The earthquake has a certain magnitude determined by a slider.
MOD	EQ	3	The earthquake can be created on any place inside or outside of the city (but within model).
MOD	EQ	4	After the earthquake, no other injuries (independent from the earthquake) occur
MOD	EQ	5	The patches in the epicenter of the earthquake are black, patches far from the earthquake are white. There is a gradient in between.
MOD	GS	1	The global state resembles all the properties that agent or objects can use or edit
MOD	GS	2	The location and severity of injured residents in a building are called in to global state
MOD	GS	3	The global state receives calls from residents, detected closed roads from ambulances and drones and the status of ambulances
MOD	GS	4	The global state keeps track of hospital occupancy