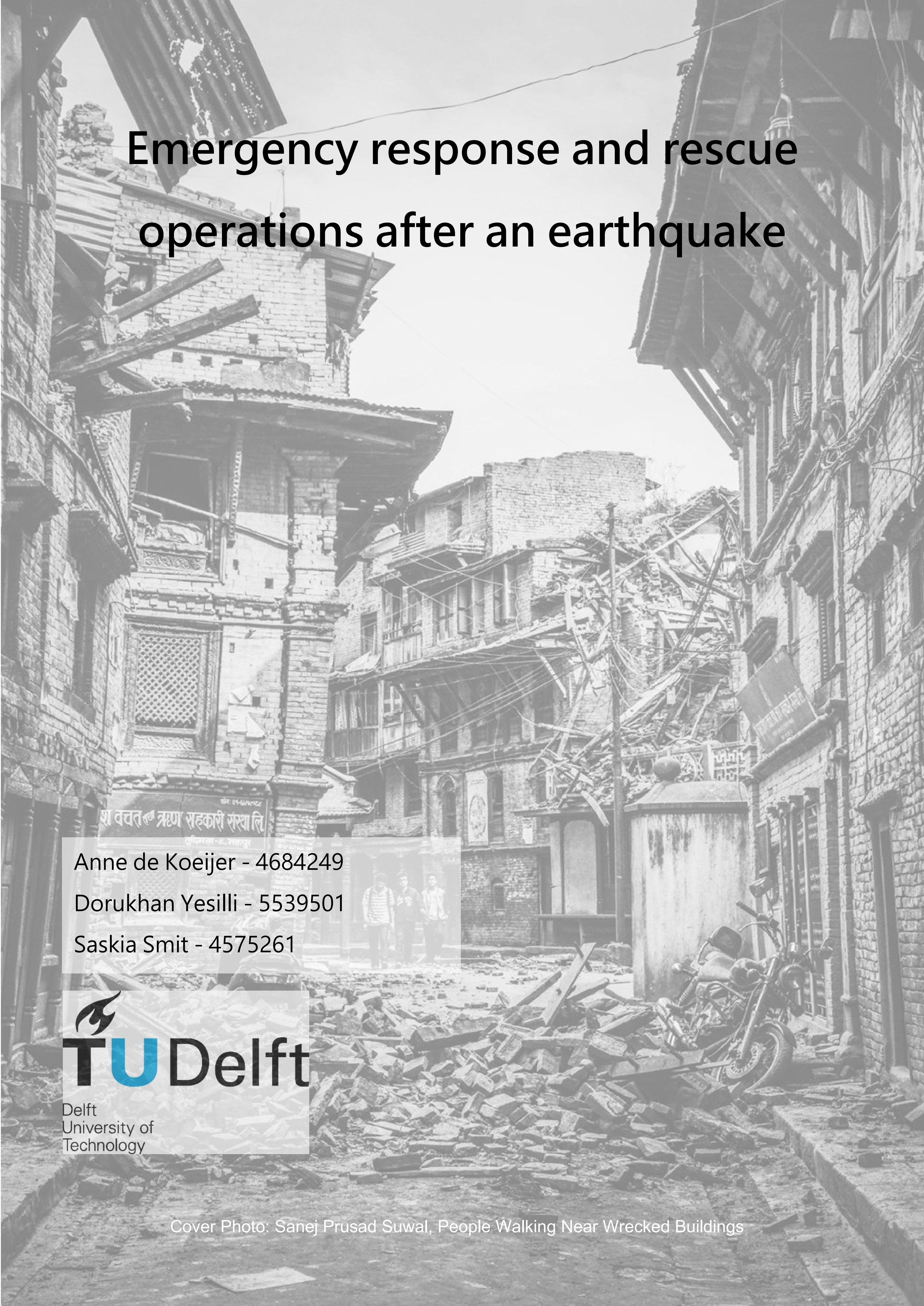

Emergency response and rescue operations after an earthquake

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Cover Photo: Sanej Prusad Suwal, People Walking Near Wrecked Buildings

Preface

This report was written for the course SEN1211 - Agent-Based Modelling. Part of this course was a group project, in which we were asked to model the emergency response and rescue operations in a city of Turin, Italy, when hit by an earthquake. We had the opportunity to do this in multi-agent modelling software Netlogo or in coding software Python with the package Mesa. We have chosen to use Python.

We would like to thank Dr.ir. Igor Nikolic and Dr. Natalie van der Wal for their contribution.

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1 - Introduction

Natural disasters like earthquakes often cause a high degree of damage. Especially in a city, which is a highly inhabited area, a lot of people may be injured or killed (Friedrich et al., 2000). Even smaller magnitude earthquakes can produce enough significant shaking such that damage can occur (Minson et al., 2021). According to Rom & Kelman (2020), most deaths and injuries are caused by building collapse, making transportation of victims to the nearest hospital an early priority.

The urban road network of a city plays a vital role in providing rescue and recovery support in disaster situations (Zhou et al., 2019). Historical experience shows that extreme natural hazards, especially earthquakes, can cause large-scale road disruptions (Schanack et al., 2012). One of the most important impacts of road network disruptions is the hindering of emergency response activities (Tak et al., 2019), which would result in more injuries and deaths. Therefore, it is important to evaluate the emergency response functionality of a city during possible earthquakes.

In this project, we will model the emergency response and rescue operations in the city of Turin, hit by an earthquake using agent-based modelling in Python (Mesa). The aim of the study is to understand the effect of an earthquake on a city and to find out what policy measures regarding emergency response could help to mitigate the effect of the earthquake. The city of Turin is hereby taken as case study. Please note that the main aim of the project is not to create a 1-1 replication of a real life earthquake disaster response case but rather, put simply, to establish a model that has agents who interact in a given grid. This ABM modelling will allow us to gain insight into following research questions and their corresponding sub questions:

1. *What is the behaviour of the model under various parametrizations, and what insight can it garner for the earthquake emergency response?*
    1.1 *How does education against earthquakes relate to injuries, deaths and recoveries in the model?*
    1.2 *How does having a higher number of steel buildings relate to injuries, deaths and recoveries in the model?*

2. *What is the influence of implementing road maintenance or trauma helicopters on the effectiveness of rescue operations?*
    2.1 *Does road maintenance ensure less gridlocks and thus, relate to a higher rate of recoveries?*
    2.2 . *Do trauma helicopters increase the number of recoveries due to not being limited by the roads and being much faster than an ambulance?*

To provide an answer to the first question, an exploratory modelling approach has been applied. Most parameters within the model will be fixed, but the certain parameters will be chosen to study their effect. The *'probability of a resident getting injured/dying due to a building's damage', 'the amount of steel buildings'* and *'the magnitude of the earthquake'* will be the experimental parameters. These parameters all influence the amount of injured/dead

people and will give insight into under which circumstances a city should increase their emergency response or prevention.
For the second question, we selected two relevant policy measures: deployment of road maintenance cars and trauma helicopters. Road maintenance cars can fix the roads that are broken due to the earthquake, and helicopters can transport residents faster and more efficiently. The model basically runs on three versions where different scenarios are tested: A version without any policy measures, a version with one of two policy measures, and a version with both policy measures.

By answering the two research questions insight can be given into possible policy measures that will prevent negative effects of an earthquake and benefit emergency response.

Hypothesis

Parameterization
A high value for the magnitude of the earthquake will increase the probability of a building's damage, which will consequently increase the amount of injured or dead people. If the city's emergency response is not fast enough or does not have the capacity, many injured people will die.
The same goes for the amount of steel buildings, only hereby how bigger the amount of steel building, how lower the probability of a building's damage. The probability of a resident getting injured/dying due to a building having high damage/collapsing will also affect the amount of injured or dead people.

The earthquake's magnitude and the building's material both affect the probability of a building getting damaged. Therefore, we assume that a scenario in which the value for the earthquake and the amount of steel buildings is both high, will have about the same results as a scenario in which both parameters have low values. In this hypothesis it is assumed that the probability of a resident getting injured/dying due to a building having high damage/collapsing will be the same for both scenarios.
The same can be said for the probability of a resident getting injured/dying. A high value for this parameter and the amount of steel buildings, will be the same for a scenario in which both are low. A high value for probability of a resident getting injured/dying and a low value for the earthquake's magnitude, will result in the same as vice versa.
It therefore is hypothesised that the parameters are all equal in effect on the amount of injured/dead people (due to the earthquake).

Policy
Road maintenance cars (RMC) will fix the broken roads so that they become available again for the ambulances to use. By implementing these RMC's ambulances will be able to reach injured residents faster. Some residents might also be unreachable due to being completely surrounded by broken roads. The RMC will make it possible for the ambulances to reach these residents. Therefore, it is hypothesised that the implementation of the RM will lead to less dead people.

Helicopters can bring injured people faster and more efficiently to hospitals, as it has a high speed and can return to any hospital it desires. Therefore the implementation of trauma helicopters could lead to less people dying due to injury.

2 - Conceptualisation

This chapter provides a description of the model. The system boundaries, description, KPI's, parameters, conceptual model and assumptions of the model will be elaborated. The conceptual model is used to build a formal model, found in chapter 3. However, there have been iterations between the formal model, the implemented model, and the conceptual model.

2.1 System boundaries

Geographic boundaries

We will model the emergency response of the city Turin, Italy, when hit by an earthquake. The system boundary is therefore the city of Turin with its inhabitants, buildings and processes. A distinction between different types of buildings is not made. The city can best be represented as a graph with nodes and links. Links being the roads, and the nodes being the intersections of the roads.

Figure 1: Aerial view of Turin

Time

In regards to time, the system will be bounded by 48 hours after the occurrence of the earthquake (the earthquake being the starting point of the system). We will observe the earthquake consequences and the emergency response to it during that time. The agents, objects and processes included in the system are described below.

2.2 Description

In the city, there are buildings and hospitals, which are distributed over the nodes. An earthquake can occur at any location and will cause damage to buildings. In this model, the earthquake occurs at the node with coordinate (0,0).

Buildings are directly affected by the earthquake’s shaking and can get severely damaged. The degree of building damage is determined by several factors, such as the earthquake magnitude, the building type and distance from the epicentre.
Each building has a number of residents living in it. The degree of building damage determines the number of injured people and deaths. For example, a stronger and closer earthquake will induce more damage to buildings, and therefore more injuries and death cases.
Roads can be closed due to debris falling from collapsed buildings. If a road is closed, ambulances cannot use it until it is fixed.
There are several hospitals in the city which will be distributed over the nodes randomly. Each hospital has ambulances that transport injured people through the road network. It picks injured people and transports them until there is no one left to pick up. If a road is closed, the ambulance cannot use it to reach a certain building and must find another route or choose another injured person to go to.
Each hospital has a capacity represented by the number of beds. If the hospital is full, no more people are accepted and ambulances cannot leave to pick up an injured person. Injured people who could not be transported to the hospital will die after some time. People will recover after spending a certain amount of time at the hospital.

Policies
The chosen policies (Road Maintenance Cars and Helicopters) can be introduced into the model. Road Maintenance Cars (RMC) will have headquarters (HQs) from which they originate from. RMCs will go to the broken roads and fix them one by one so they become available again. Helicopters will fly over to an injured person to pick them up and fly them to the nearest hospital. It will do so one by one till there is no one to pick up left.

2.3 Conceptual model

In Appendix A a visual representation of the conceptual model and its explanation can be found. The conceptual choices deduced from the conceptual model regarding which agents, processes and interactions are described below.

2.3.1 Agents, Processes and Interactions

There will be in total six Agents: Residents, Ambulances, Buildings, Hospitals, Road Maintenance Cars and Helicopters. Residents, Ambulances, RMCs and Helicopters are modelled as agents as they will require personal attributes, moving over the grid and have functions to perform every step. Residents will be kept simple: they will all be subject to the same attributes and distributions, and therefore they will all be the same. Buildings and Hospitals do not move, but will still be agents as this allows them to have attributes and, more importantly, to be placed on the grid.
Roads will not be modelled as agents (or objects) as they are built-in in the graph.

Table 1 shows processes that shall occur in the model. Which agents interact during these processes is also specified. Every process is a reaction to another process (‘Buildings get damaged being an exception). For example, people are transported to the hospital because they got injured.

Table 1: Conceptual Agents and their interactions

Process	**Interaction**
Buildings get damaged	-
Roads close to collapsed building	Buildings and the grid
People get injured/die	Buildings and the residents
People are transported to hospitals	Ambulances and the residents
People get cured	Hospitals and the residents
Policy: Road Maintenance Cars	RMC's and the grid
Policy: Helicopters	Helicopters and the residents

2.3.2 Parameters

The model will require various input parameters (e.g. number of buildings or ambulances per hospital). These consist of fixed parameters, which will be the same for every run of the model, and experimentational parameters, which vary corresponding to the intended experiment. The chosen experimentational parameters are given below in table 2. These experimental parameters will be used to answer the first research question
The full list of the parameters, with their explanation and values, can be found in Appendix B.

Table 2: Experimental parameters

Experimental parameter	**Unity**	**Value**
Probability of resident getting injured when building has collapsed	[%]	0, …, 100
Probability of resident dying when building has collapsed	[%]	0, …, 100
Probability of resident getting injured when building has a high amount of damage	[%]	0, …, 100
Probability of resident dying when building has a high amount of damage	[%]	0, …, 100
*Probability of a building being steel**	[%]	0, …, 100
Earthquake magnitude	Richter scale	0, .., 10

2.4 KPI’s

The research questions include understanding and mitigating the effects of the earthquake. Therefore, the first key performance indicators are set to be the number of injured people, the number of deaths and the number of recoveries. We also want to track some important variables for a deeper understanding of the bottlenecks during the emergency response time after an earthquake, such as the amount of times a hospital has reached full capacity.

The list of the key performance indicators is as follows:

- Number of deaths
- Number of injured
- Number of recoveries
- Warning count for ‘ambulance cannot leave’ due to no capacity

2.5 Assumptions & Model reductions

Certain assumptions and model reductions have been made to simplify the model, and therefore make it more clear. This simplification has been done due to time and resource limitations. Below the extensive list of assumptions and model reductions is described.

Table 3: List of Assumptions and Model Reductions

Assumption/Model reduction	Explanation
Map is scaled down	The graph that was provided to us was a slightly scaled down version of the real dimensions of Turin. Due to this, and due to time and resource limitations, various parameters have also been scaled down. In our model there will be only 8000 residents living in Turin, and speed of the vehicles has been adjusted to the map size
Earthquake at (0,0)	For simplicity, the earthquake can only occurs at the node with coordinate (0,0) in the roadmap of Turin
One building per node	In our model we assume that the maximum number of buildings per node is limited to 1. This is done for simplicity
No different types of buildings	In the model you will only have buildings, hospitals and HQs. A variation in buildings, such as schools, does not exist.
Probability of brick or concrete	The probability of brick and concrete is the remaining value of the steel probability divided by two. (If, for example, the probability for steel is 0.4 the other ones (brick and concrete) will be the same weights (both 0.3)).
Same number of residents for each building	Each building will have the same number of residents (20).

Residents do not move during an earthquake	In the model, residents don't leave the buildings. It is assumed that people will be too injured to move.
Every resident is equally vulnerable to the earthquake	In the model every resident is the same. For example, a person's vulnerability to injury is not taken into account. Therefore all residents have an equal chance of injury.
Degree of building damage	A building can only have one of three degrees of damage: 'intact', 'highly damaged' and 'collapsed'. No in-between.
Hospitals do not get damaged	For simplification it is assumed that hospitals will never collapse due to an earthquake.
Ambulances can only go to their own hospital	While ambulances are normally located at specific hubs, in our model the ambulances will be initiated at the hospitals. Ambulances pick up injured residents and bring them back to the hospital where they came from.
Residents cannot die in the ambulance	For our model it is assumed that people will receive enough aid in the ambulances to not die in them. Recovery will not start until they are in the hospital
Residents always recover at the hospital	When a resident makes it to a hospital, it will always recover. In reality people can also die in a hospital due to their injuries
Ambulances do not leave when hospital capacity is full	In our model an ambulance will check if there is enough capacity in the hospital to decide if it can leave. If there is it reserves a bed for the injured person
No different degrees of injury	A resident can only be alive, injured or dead, nothing in between. Therefore, every person has the same recovery time, and there are therefore no urgent cases.
Movement of agents	An agent advances through a node if it can satisfy the length between its current node and the next node it will step into in 1 step. Or else it will wait until the time is full with respect to length/speed to advance.
RMC: continuously can fix roads	A RMC never has to go back to HQ to collect new supplies, it can constantly continue to fix roads
Helicopter	The helicopter calculates its path using the lengths of the roads instead of the Euclidean distance.

4. Formalisation

In this chapter a formalisation of the conceptual model is presented. For more detail on the formalisations, view Appendix B.
The model is made in python using various libraries and packages, among the most prominent being Mesa and Networkx.

4.1 Initialization model

With the use of the Networkx library in python, the city of Turin is represented in the model by a graph with links and nodes (Appendix B1). There are a number of hospitals that are randomly placed across the nodes, having no more than one hospital node. Every hospital has the same capacity. At every hospital a number of ambulances are generated, each having the same capacity. Besides hospitals, a number of buildings are also randomly distributed across the nodes of the city. A building will not be placed on a node where there is a hospital or another building. When generated, each building is assigned a material and a size according to material- and size probabilities. A number of residents reside in each building, which are generated after the generation of the building.
Residents, ambulances, buildings and hospitals are all modelled as Agents. The model "keeps track" of the existing residents, hospitals and roads during the runtime.
In figure 2 and 3 an overview is given of the initialisation of the Agents.

The earthquake with a certain magnitude occurs at the node with the coordinates (0,0). After the earthquake has occurred, buildings get damaged, people get injured, and roads collapse. These processes happen within the model initialisation (step 0) (see 4.2.1). After this initialization the model runs per step/tick and its processes of the Agents are conducted (see 4.2.2).
The model runs per step/tick, each step/tick being one minute.

Policy part
In the same way as the hospitals and buildings, HQs for the Road Maintenance Cars (RMC) and HQ's for the helicopters are randomly placed. Again, these HQs will not be placed on nodes where other HQs, buildings or hospitals are already located. At each HQ, a number of RMCs or Helicopters respectively will be generated. RMC and Helicopters are also modelled as Agents. The Helicopters are assigned a capacity of 1.

View Appendix B2 for the sketch of the code of the model initialisation.

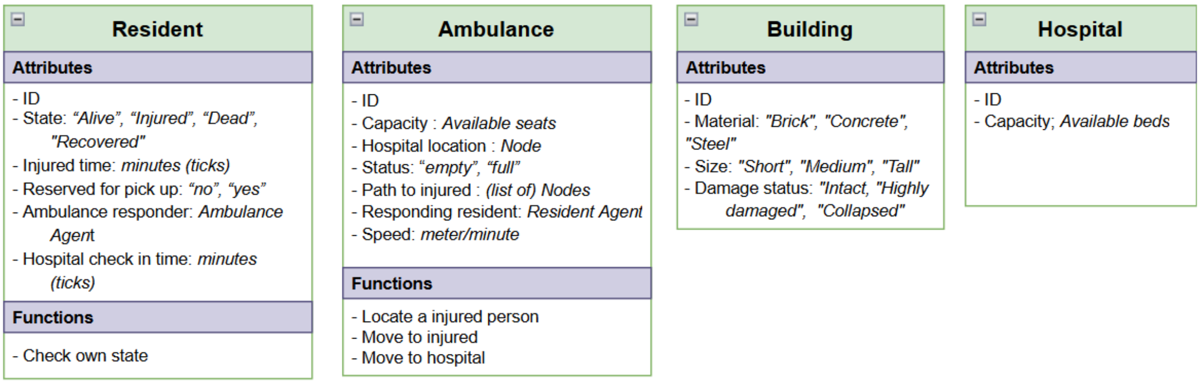


Figure 2: Formalisation of Agents: their attributes and functions

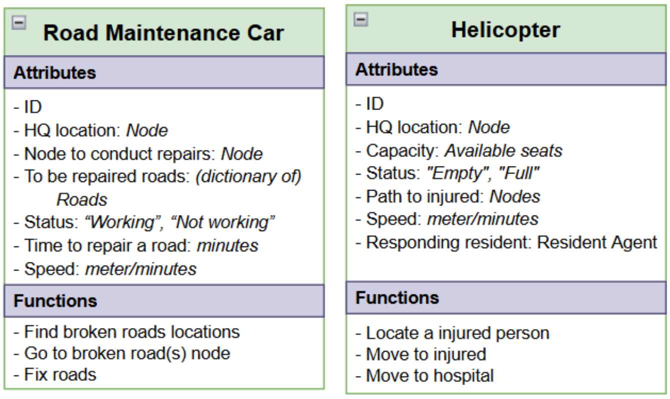


Figure 3: Formalisation of Policy Agents: their attributes and functions

4.2 Processes

4.2.1 Processes during Initialisation

Buildings get damaged

To determine the amount of damage a building suffers (the damage status), damage probabilities are determined:

➢ Building Damage Probability distribution:

- $CollapseProbabilityCP = 0.7 \times VM + 0.1$
- $HighdamageProbabilityHP = -0.15 \times VM + 0.3$
- $NoDamageProbabilityNP = -0.55 \times VM + 0.6$

The value of a probability depends on how vulnerable a building is to an earthquake (*VM*). The vulnerability is determined by its *Building Type* (TM), *Building Height* (HM), *Distance from epicentre* (DM) and *Earthquake intensity* (EM). All these factors have a value between 0 and 1.

➢Building Vulnerability VM:

$VM = TM \times HM \times DM \times EM$

The sum of the three Building Damage Probabilities account to 1. By using a random choice function, the damage status of a building determined (“Intact”, “Highly damaged”, “Collapsed”) View Appendix B3 for more detail on the Building Damage Probability distribution.

People get injured/die

Depending on the damage of a building, probabilities for a resident to be “Alive”, “Injured”, or “Dead” is determined. When a resident is injured, they will die after a certain amount of time. By checking their status every tick they can determine how long they have been injured and if they are dead. When a resident is in an ambulance or at the hospital, it cannot die. If a resident is dead they are removed from the system. If a resident is injured they are also added to the model’s list of injured residents.

Roads close to collapsed building

Depending on the damage of a building, probabilities for a Road to be “Intact” or “Broken” is determined. If a road is broken it will be removed from the graph/grid. The road with its adjacent nodes and the length of the road is saved to a dictionary for use by the Road Maintenance Cars.

4.2.2 Processes during Model run

Ambulances transporting injured people

This process exists out of various functions within the Ambulance Agent: Locating an injured person to go to, moving to said injured person, and ultimately moving back to its original hospital. In the latter function a respective Resident Agent is “moved along” with the ambulance.

To locate an injured person an ambulance calls upon the model’s list of injured people, and selects those that are not “reserved” for pick up. By choosing the shortest of the shortest paths to each resident (using the Dijkstra method), an injured resident to pick up is chosen. This resident’s status is set to “reserved” so no other ambulance will try to pick up the same resident.
Node for node the ambulance over the shortest path of its injured resident. The time an ambulance waits before it goes from one node to the next, is dependent on its speed and the node length.
When an ambulance arrives at the intended injured resident, the ambulance's status becomes “full", and it will start moving back to its hospital through the shortest path. The resident “moves along” as it is given the same path back to the hospital, and by making it move as fast as the ambulance.

People get cured

When an ambulance arrives at its hospital, the hospital check in time of the transported resident gets noted. By using the check own status function, the resident monitors when the time of the model surpasses the time of check in plus the needed recovery time. When it does -when they are “recovered”- they are removed from the model and an available bed frees up at the corresponding hospital.

Policy: Road Maintenance workers fixing roads

A RMC starts off with locating the nodes which are adjacent to the broken roads/edges. It does this by using the aforementioned dictionary containing the broken roads. By calculating the shortest path to all these nodes, the nearest node is selected. Only nodes are taken into consideration that the RMC can reach (and are not unavailable due to broken roads). This node is 'reserved' so no other RMC goes to it.
Node for node, the RMC moves the shortest path to the intended node. Here again, the amount of time before a RMC reaches the next node is dependent on the road length and its speed. When arrived at the intended node, the RMC starts working. It takes a certain amount of time for the RMC to fix one road, after which the edge is returned to the graph and the RMC moves on to other possible broken roads at that node. If there are no broken roads left at the node, the RMC "stops working", and looks for new roads to repair.

Policy: Trauma helicopter

The Helicopter finds and "reserves" the nearest injured person in an identical way as the ambulance. The helicopter, however, does not need to move over the edges but can fly to the injured person. By calculating the shortest path distance to the resident's node and the helicopter's speed, it is determined how long until the helicopter "arrives" at the intended node. When it arrives, the helicopter's status becomes full, meaning it will travel to the nearest hospital with capacity available. It finds the nearest hospital, by selecting the shortest path. The corresponding hospital's number of available beds will decrease with one. The resident is transported by the helicopter by having the resident move to the corresponding hospital node at the same time as the helicopter.
When the helicopter arrives at the hospital, it starts searching for a new injured resident. If there are no residents the helicopter returns to/stays at its HQ.

5 - Verification & Validation model

5.1 Verification of model

During verification, we check whether the empirical model matches the conceptual model. This includes checking whether the events and processes discussed in the model conceptualisation have also been properly implemented. Because we do not have a visualization of the model, this step is essential to see if the model is doing what it is intended to do.

By implementing a print function in the corresponding parts of the code, it will be possible to verify the aforementioned processes. Figure 4 shows an example of how it is implemented in the verification of the initialisation of the model.

```
for i in range(self.num_hospitals):
    a = Hospital('Hospital' + str(i), self)
    self.schedule.add(a)
    self.list_of_hospitals.update({'Hospital' +  str(i) : a })
    location = self.random.choice(list(self.streets))
    while self.grid.is_cell_empty(location) == False:
        location = self.random.choice(list(self.streets))
    self.grid.place_agent(a, location)

    print('placed hospital ', a.unique_id, ' on node ', a.pos)

    for j in range(self.num_ambulances):
        b = Ambulance('Ambulance ' + str(j) + ',' + str(i), location , a.available_beds, self)
        self.schedule.add(b)
        self.grid.place_agent(b, location)

        print('placed ambulance ', b.unique_id, ' on node ', b.pos)
```

Figure 4: Example code to verify model: Verification of the model's initialisation

Initialisation of the model

The model is run for one step. The model should create 400 buildings each with 20 residents (8000 residents in total), 20 hospitals each with one hospital, 1 RMC HQ with 1 RMC, 1 helicopter HQ with 1 trauma helicopter. No buildings, hospitals or HQs should have the same node.

```
placed hospital  Hospital0  on node  7413
placed ambulance  Ambulance 0,0  on node  7413
placed hospital  Hospital1  on node  8886
placed ambulance  Ambulance 0,1  on node  8886
placed hospital  Hospital2  on node  9991
placed ambulance  Ambulance 0,2  on node  9991
placed hospital  Hospital3  on node  7042
placed ambulance  Ambulance 0,3  on node  7042
```

```
placed building  Building 0  on node  8831
placed resident  Resident 0 from Building 0  on node  8831
placed resident  Resident 1 from Building 0  on node  8831
placed building  Building 399  on node  9117
```

```
placed RMC HQ  Road Maintenance HQ  0  on node  6741
placed RMC  Road Maintenance Car 0 from Road HQ 0  on node  6741
placed helicopter HQ  Disaster Response HQ 0  on node  14364
placed helicopter  Helicopter 0 from Helipad in Disaster Response HQ 0  on node  14364
The number of hospitals:  20 Total number of ambulances:  20 The number of buildings:  400 Total number of residents:  8000
```

Figure 5: Verification results of model initialisation

The outputs of the print function (figure 5) verify the initialisation of the model.

Buildings get damaged

Due to the earthquake each building should calculate its vulnerability (VM), and depending on that change its damage status.

```
Building material concrete
Building vulnerability VM:  0.004968191111179815
Building 10 its damage status is intact
Building material brick
Building vulnerability VM:  0.06414498747489746
Building 11 its damage status is collapsed
Building material concrete
Building vulnerability VM:  0.008850364580750376
Building 12 its damage status is collapsed
Building material concrete
Building vulnerability VM:  0.04949968246548933
Building 13 its damage status is intact
```

Figure 6: Verification results of buildings get damaged

The first line mentions the building material, the second the resulting vulnerability of the building, and the third line gives the result of the earthquake to the building's status (figure 6). The buildings indeed get damaged.

People get injured/die

At the start of the model, after the buildings have gotten damaged, residents of said buildings could get injured or die. This is verified with the following figure.

```
Building 1 has status collapsed
Resident 0 from Building 1 has now as status alive
Resident 1 from Building 1 has now as status injured
Resident 2 from Building 1 has now as status injured
Resident 3 from Building 1 has now as status dead
Resident 4 from Building 1 has now as status dead
Resident 5 from Building 1 has now as status injured
Resident 6 from Building 1 has now as status injured
```

Figure 7: Verification of People get injured (Part 1)

To verify if residents also die after a certain time, the death time has been lowered. The figure below verifies this.

```
This is step: 32
The time of Resident 4 from Building 134  being injured:  0 (model time:  32 ). The death time is: 31.099761441989763 . I am now dead
The time of Resident 7 from Building 328  being injured:  0 (model time:  32 ). The death time is: 31.272159501913574 . I am now dead
```

Figure 8: Verification of People get injured (Part 2)

Roads close to collapsed buildings

There is a possibility that a road gets broken if the building near the road gets damaged. The figure below first shows the amount of roads in the graph without the earthquake. Below it is the amount of roads after the earthquake. The number has decreased and therefore the process is verified.

```
Amount of roads before earthquake:  34626
Amount of roads after earthquake:  34438
```

Figure 9: Verification of Roads close to collapsed buildings

Ambulances transporting injured

The below figure shows that an ambulance has found a resident that is injured, has reserved it, and the ambulance is moving towards it. It prints when an ambulance has arrived at the intended resident.

```
I am  Ambulance 0,16  Im located at node  5723 and i am going to pick up Resident 3 from Building 240 . This resident is located at  1801 , and has as status
served status  injured yes
I moved to 5722 in this step.
I am  Ambulance 0,12  Im located at node  6297 and i am going to pick up Resident 0 from Building 117 . This resident is located at  6243 , and has as status
served status  injured yes
I moved to 6296 in this step.
I am  Ambulance 0,2  Im located at node  5815 and i am going to pick up Resident 0 from Building 263 . This resident is located at  5815 , and has as status and res
erved status  injured yes
Ambulance 0,2 has arrived at injured resident
```

Figure 10: Verification result of Ambulances transporting injured (Part 1)

Now the ambulance must go back to the hospital with the resident. The figure below verifies this.

```
Ambulance 0,2  is going back to Hospital now at node 2165 Resident is moving along as his node is  2165
Ambulance 0,2  is going back to Hospital now at node 2166 Resident is moving along as his node is  2166
```

Figure 11: Verification result of Ambulances transporting injured (Part 2)

People get cured

The recovery time of a resident is 45 minutes. The model will start counting how long a resident has been in the hospital the step after it is admitted to the hospital.

```
I, Resident 0 from Building 131 have recoverd beacuse my hopital check in time was  25 and right now it is:  71
```

Figure 12: Verification result of People get cured

RMC

For the verification of the RMCs, the time to fix a road has been lowered to 30 minutes. The figure below shows that the RMC indeed goes to a node with broken roads and repairs all its roads.

```
The RMC has chosen to go to this node to repair its roads:  3652
The roads to be repaired there and their attributes (roadID and lenght) are:  {(3652, 3653): [3691, 26.62286], (3652, 0): [23266, 26904.49854]}
RMC is located at  4518
RMC has moved to 4517 in this step.
```

```
RMC has moved to 3652 in this step.
RMC has arrived at  3652 , so it will start working on the roads
```

Figure 13: Verification results of RMC

Helicopter

In the same manner as the ambulance, the processes of the helicopter are verified. The figure below shows how a helicopter finds an injured person and flies to them, to consequently transport them back to the hospital. You can see that it takes a while (step 0 → step 3) before the helicopter arrives at the injured resident. That means it took the helicopter 3 minutes to fly.

```
This is step: 0
I am  Helicopter 0 from Helipad in Disaster Response HQ 0  Im located at node  9074 and i am going to pick up <__main__.Resident object at 0x000001FFAFBBB5B0> .
 This resident is located at  8953 , and has as status and reserved status of injured yes
This is step: 3
I am  Helicopter 0 from Helipad in Disaster Response HQ 0  Im located at node  9074 and i am going to pick up <__main__.Resident object at 0x000001FFAFBBBC10> .
 This resident is located at  8953 , and has as status and reserved status of injured yes
Helicopter moved to 8953 in this step.
Helicopter 0 from Helipad in Disaster Response HQ 0 has arrived at injured resident
```

Figure 14: Verification results of Helicopter (Part 1)

The helicopter then chooses the nearest hospital to fly back to.

```
Helicopter is going to  Hospital1 at node 9000
Helicopter moved to 9000 and is therefore in the hospital.
```

Figure 15: Verification result of Helicopter (Part 2)

5.2 Validation of model

When validating a model one asks themselves the question “did we build the right thing?”. This can be answered using different criteria. Due to simplification of the model and the fixed input parameters -for example, the model having only 8000 residents when in reality Turin has little less than 2 million-, the results of the model will not comply with reality. However, the main assumption of this research is that the aim is to build *a model* and interpret its results and not necessarily create the most realistic earthquake simulation. Therefore, to validate the model, it will be examined if the relative changes in parameters are realistic.

In our model when we increased the magnitude of the earthquake from 0.2 to 0.8, the number of injured people on average also increased 300 , and the dead by 100. Literature into the relationship between the earthquake magnitude and its casualties have not been able to form a conclusive function or distribution, as it is influenced by many various parameters (Ferreira et al., 2013).

Literature also states that a high level of a building's resistance can result in up to 50% less injuries than buildings with low earthquake resistance (He et al., 2021). When viewing our models results it is seen that although this is the case, the output of the number of injured are not quite sensitive to the input of the steel probability. This is however understandable as the process behind the choice of whether a building is concrete, steel or brick happens through considering different weights during the initialization phase of the model. The steel probability that is input to the model determines the other weights too. If the steel probability in our low steel case is about 0.4 (as denoted in Appendix D) it means that there is an equal probability of 0.3 for the building to be initialized as a concrete or a brick building. Thus, our model is not quite sensitive to the decrease in the percentage of steel buildings as there is always an inherent bias in our experiments to having higher amounts of steel buildings.

Due to time limitations, it was not able to test other parameters within the model.

6 - Experimentation

This section details the experimentation and analysis that has been conducted on the working model. The section is divided into mainly 2 categories mainly depending on whether the policies have been applied or not. Appendix D gives exact information on what the parametrization was for each of the scenarios and also shows their corresponding codes to run in the model_run_base.py file. It could also be seen in Appendix D that the first experimentation setup has been regarded as the base case where the residents have high earthquake awareness, in other words, are educated regarding earthquakes and are also living in buildings that are mostly steel. The experimentations will be presented by first mentioning the setup, then the expectations of the specified experiment and then the analysis and contrast.

6.1 Hypothesis

Our hypotheses are divided into 2 categories, mainly: hypotheses with regards to the changing parametrization in the base case and hypotheses that are concerning policy implementation on the base case. These hypotheses establish themselves the sub questions that are mentioned prior in the introduction part of the report. The sub questions that are about the changing parametrization allow us to answer the first research question and are as follows:

1.1. How does education against earthquakes relate to injuries, deaths and recoveries in the model?

Corresponding Hypotheses:

- Higher education, meaning awareness against earthquakes by the residents, should decrease the proportion of the number of dead people after the first moments of the earthquake
- Higher education should have less amount of people injured

1.2. How does having a higher number of steel buildings relate to injuries, deaths and recoveries in the model?

Corresponding Hypotheses:

- High number of steel buildings should lead to less collapsed buildings and thus less people dead overall, moments after the earthquake
- High number of steel buildings should lead to less injured people.

Please notice that both sub questions are meant as exploratory experiment setups that can lead to an understanding of the dynamics of how the building material and resident's earthquake awareness change the number of casualties within the model. This is quite crucial as this would lead to other policy implications such as recommending the municipality to only give house building permits to companies if the building materials are composed of a sufficient amount of steel, or to create budgets for resident education programs against earthquakes in forms of festivals or mandatory teaching to students etc.

The second category are hypotheses that establish themselves as sub questions for the second research question that is about implementing policy measures and are as follows:

2.1. Does road maintenance ensure less gridlocks and thus, relate to a higher rate of recoveries?

Corresponding Hypotheses:

- *Road Maintenance Workers should fix roads, in turn, reducing the length of the shortest path that the ambulances can take which would lead to higher number of recoveries and reduction in the number of injured.*

2.2. Do trauma helicopters increase the number of recoveries due to not being limited by the roads and being much faster than an ambulance?

Corresponding Hypotheses:

- *Trauma helicopters should increase the number of recoveries and cause a reduction in the number of injured.*

These hypotheses are quite straightforward and give insight into whether there is good enough evidence to conclude that spending budget on helicopters or road maintenance is a good way to effectively contain a disaster and secure the injured people who are affected by it.

6.2 Experimental setup

Experimental setup will be described again in two categories, highlighting differences between scenarios within each category. These categories are again related to: ones that are about parametrization and those about policy implementation. The former will be represented as a scenario analysis and the latter will be represented as a testing for policy measures.

6.2.1. Scenario Analysis

The table below puts the Appendix D, which is in numerical values, into words. The statistics of 1 replication from each scenario is given in Appendix E for completeness. The main value of this section comes from the comparison and contrasting of the scenarios 1.1 vs 2.1 and 1.1 vs 3.1 as these give proper insight into whether steel or education have an impact on the output and thus answer our hypotheses. Please note that in the table below the Education refers to the amount of knowledge that Residents have against Earthquakes, namely their earthquake preparedness. This decreases the chance that they are dead for high damage buildings drastically and also for a moderate chance for collapsed buildings. The other columns are self-explanatory and refers to the parameters passed to the model.

Table 4: Scenario setup

	Education	**Building material**	**Earthquake magnitude**	**Base Case?**
Scenario 1.1	High	Higher Amount of Steel	Low	Yes
Scenario 1.2	High	Higher Amount of Steel	High	No
Scenario 2.1	High	Lower Amount of Steel	Low	No
Scenario 2.2	High	Lower Amount of Steel	High	No

Scenario 3.1	Low	Higher Amount of Steel	Low	No
Scenario 3.2	Low	Higher Amount of Steel	High	No

Scenario 1.1 vs 1.2

Earthquake Magnitude is working + Number of Broken Roads difference + Injured Difference

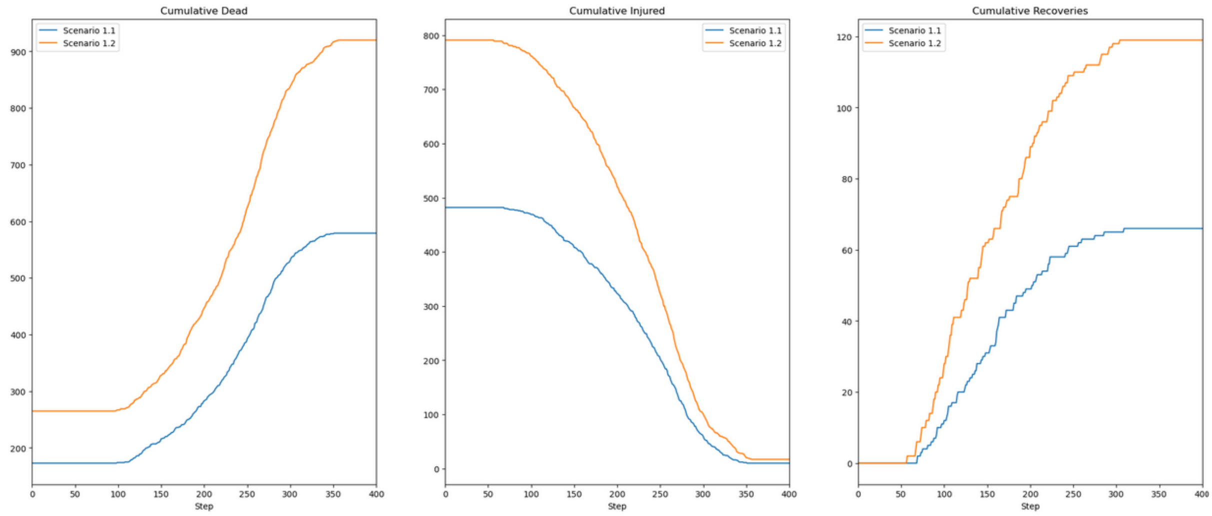


Figure 16: Comparison KPI's of scenario 1.1 and scenario 1.2

The expectations in contrasting these two scenarios were that this was the first validation of whether the earthquake magnitude was working properly and has been translated into the code or not. After the initialization of the earthquake there are more dead people at the start in scenario 1.2 (high earthquake magnitude) compared to scenario 1.1 (low earthquake magnitude). The amount of difference of the dead in the two scenarios is about 200 which leaves no question with regards to randomness. The cumulative injuries in Scenario 1.2 are also quite higher compared to 1.1 which supports the previous fact.

Scenario 1.1 vs 3.1

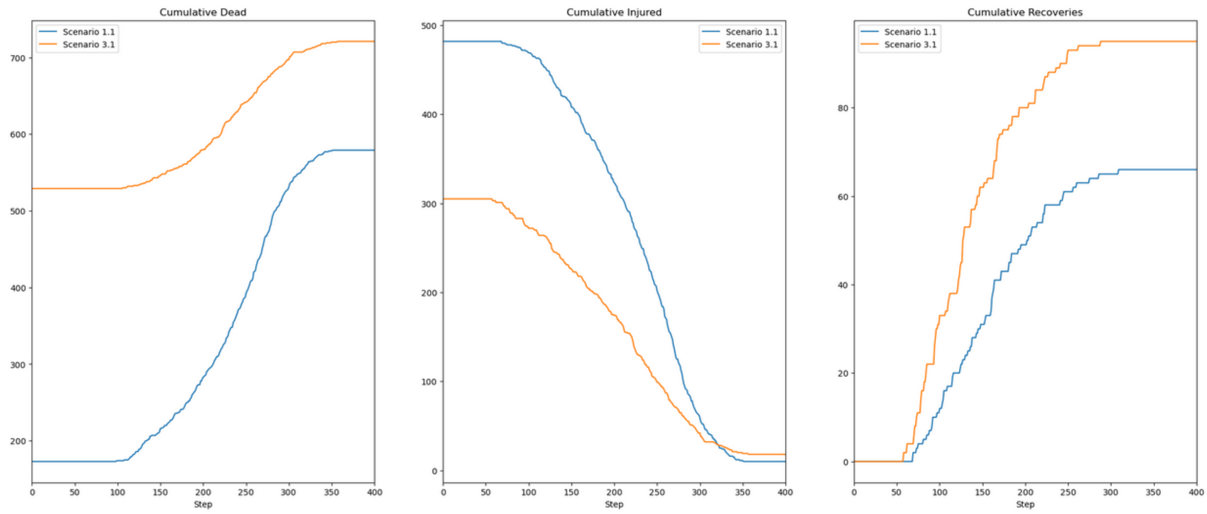


Figure 17: Comparison KPI's of scenario 1.1 and scenario 3.1

The main reason that these two scenarios are compared is to understand how the relationship between the earthquake preparedness, namely the education towards earthquakes relate to the number of dead, injured and recoveries. This is also denoted in the first sub question that was denoted in the beginning of this section. The hypotheses created for the answering of the sub question were:

- Higher education, meaning awareness against earthquakes by the residents, should decrease the proportion of the number of dead people after the first moments of the earthquake
- Higher education should have less amount of people injured

In regards to the first hypothesis in the moments after the earthquake there is a significant difference in the number of dead residents. Scenario 1.1 which has residents who are high educated have much less deaths compared to Scenario 3.1 that is composed of residents with lower earthquake preparedness. It is quite interesting that the number of dead increases much more steeply in Scenario 1.1 but can be entirely attributed to 20 ambulances not being enough to save 600 injured people. Remember that, residents die if they are not saved in the specified amount of time. Therefore the first hypothesis is supported by the output of the model.

For the second hypothesis, scenario 1.1 (high education) has quite a significant difference and is higher in the number of injured residents right after the earthquake than Scenario 3.1(low education). This is entirely understandable as more people are proportionally injured rather than being dead in the high education scenario as the education cannot substitute for full protection but can minimize the critical health consequences of earthquakes. The trends follow the same steepness and again have the same reasoning as the trend in deaths. Thus the second hypothesis is wrong and is not supported by the output, however it is understandable why such behaviour is prevalent.

For recoveries it is quite interesting to see that Scenario 3.1 outperforms 1.1. The more education of the citizens does not increase the number of recoveries as there is no correlation between the processes of recovery and the resident response in the model. (Also denoted in limitations)

Thus the first sub question is answered as: higher education against earthquake preparedness shows itself as a lower amount of deaths but higher amount of injuries (due to the proportion difference) in the outcome of the model.

Scenario 1.1 vs 2.1

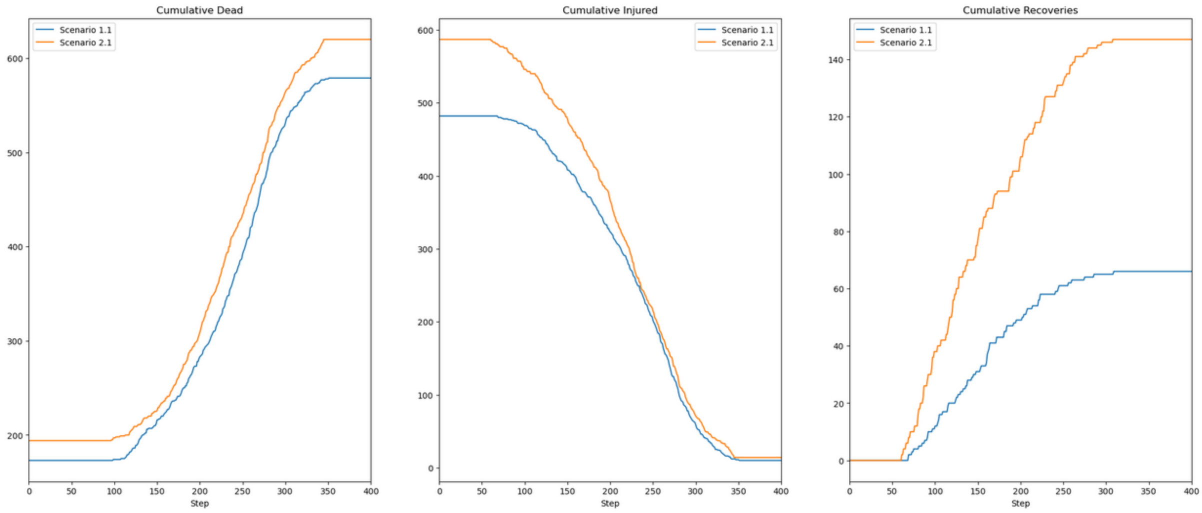


Figure 18: Comparison KPI's of scenario 1.1 and scenario 2.1

The comparison between 1.1 and 2.1 is quite important as it will give insight into replying the two hypotheses for the second sub question for the main research question denoted in the beginning of the section. These hypotheses were:

- High number of steel buildings should lead to less collapsed buildings and thus less people dead overall, moments after the earthquake
- High number of steel buildings should lead to less injured people.

In regard to the first hypothesis it could be seen that the higher number of steel buildings (scenario 1.1) relates to the lower number of deaths right after the earthquake which supports our hypothesis.

The steepness of the cumulative dead curves are almost similar whereas the steepness of the cumulative injury curve in Scenario 2.1 go down much faster due to having more recoveries in less amount of steps.

For the second hypothesis, it could be seen that higher amounts of steel buildings decrease the amount of injured people right after the earthquake. Then the second hypothesis is also true.

Comparatively however, it is quite interesting to see that the Scenario 2.1 where there are much more injured people outperforms 1.1 with regards to recovery. This could be due to that in the model more injured people to be saved, which may correspond to shorter paths as there is a higher chance that ambulances will have nodes that are collapsed, because they were not made out of steel, closer to them and thus decrease the amount of time it takes to get the residents into hospitals.

Then the second sub question is answered in the following way: more steel buildings directly relate to the decrease in deaths and the decrease in injuries right after the earthquake, however, it does not necessarily mean that it will have an increasing effect on the number of recoveries with respect to the data from the output of the model.

With both sub questions answered we can now answer the first research question that is based on exploratory analysis, namely, “*What is the behaviour of the model under various parametrizations, and what insight can it garner for the earthquake emergency response?”* The answer then becomes, with different parameterizations it has been seen that the model behaves with regards to expected outcome especially at the start when there is a higher awareness by residents and more number of steel buildings. These relate to lower death numbers but in some cases higher injuries. The emergent behaviour seen is that the recoveries are not correlated with these parametrizations at all and is interesting to see as the injury probability of an individual that changes with respect to their preparedness and whether they live in steel buildings do not matter in this aspect. Another interesting note is that even though steel buildings do not collapse as often, the scenario with less steel outperforms the more steel buildings scenario.

6.2.2. Testing Policy Measures

	Policy 1 (Road M)	**Policy 2 (Helicopters)**	**Case**
Scenario 4	Yes	No	Base Case
Scenario 5	No	Yes	Base Case
Scenario 6	Yes	Yes	Base Case

Scenario 4 : Road Maintenance Cars

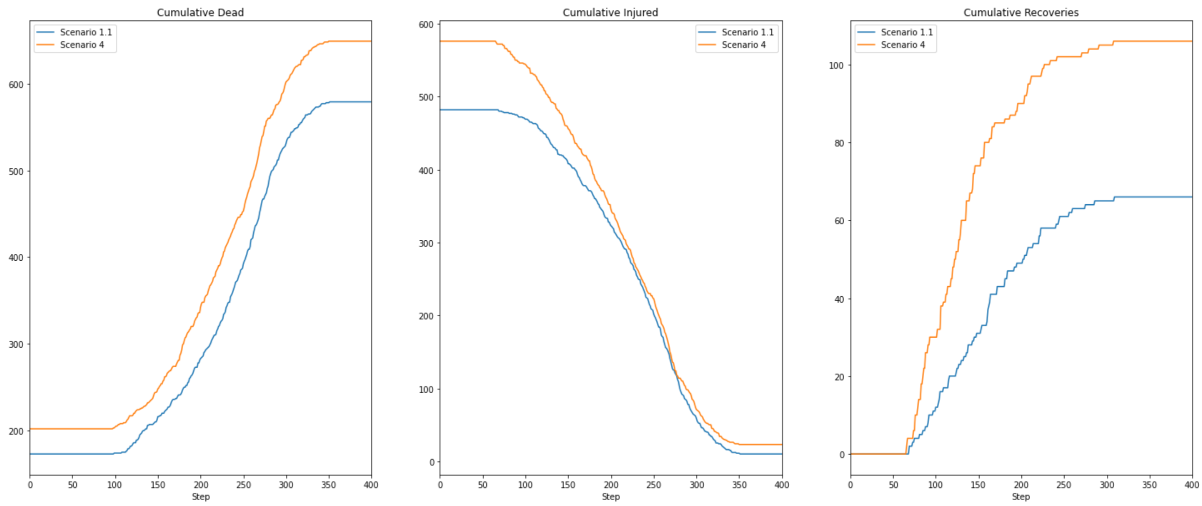


Figure 19: Comparison KPI's of scenario 1.1 and implementation of RMC

The main sub question that is related to the Road Maintenance Cars is whether the introduction of the policy corresponds to less gridlocks and thus a higher rate of recoveries. The hypotheses introduced to answer the sub question are:

- *Road Maintenance Workers should fix roads, in turn, reducing the length of the shortest path that the ambulances can take which would lead to higher number of recoveries and reduction in the number of injured.*

In response, it could be seen that in the long run the number of recoveries in Scenario 4 (Policy Implementation) has quite high steepness in the curve of recoveries compared to Scenario

1.1. Implying that the ambulances can go quite fast to the residents and bring them back to the hospital. Considering that this is prevalent throughout replications, the randomness is mitigated and therefore there is support for the hypothesis.

Scenario 5 : Trauma Helicopters

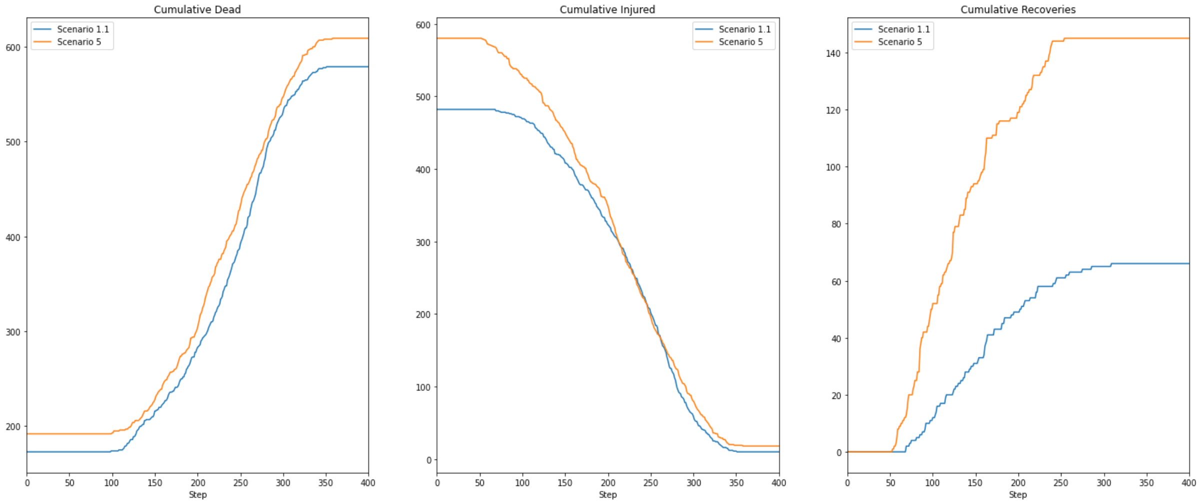


Figure 20: Comparison KPI's of scenario 1.1 and implementation of helicopter

The main sub question that is related to the Trauma Helicopters is whether the introduction of the policy corresponds to less gridlocks and thus a higher rate of recoveries. The hypotheses introduced to answer the sub question are:

- *Trauma helicopters should increase the number of recoveries and cause a reduction in the number of injured.*

This is prevalent in the amount of recoveries being much steeper than in scenario 1.1 even though there isn't much difference in the amount of dead and injured at the beginning of the scenario. This supports the hypothesis that trauma helicopters increase the number of recoveries and cause a reduction much faster in the number of injured. Please note that the base cases are the same and that is the reason that they are quite similar in cumulative dead and injured graphs however, the recoveries outnumber by a fair margin. Indicating randomness to not be an issue.

Scenario 6 : Road Maintenance Cars & Helicopters

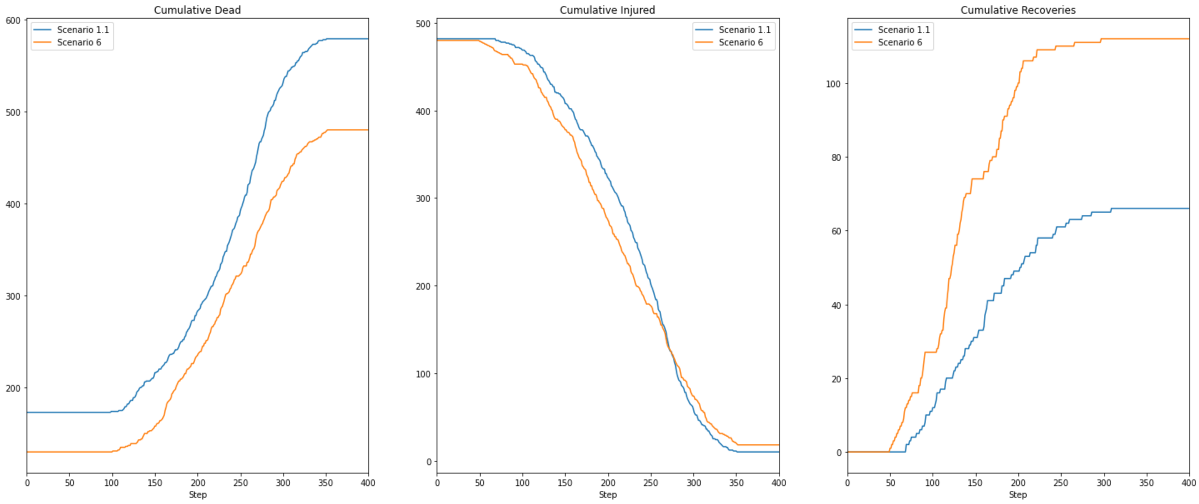
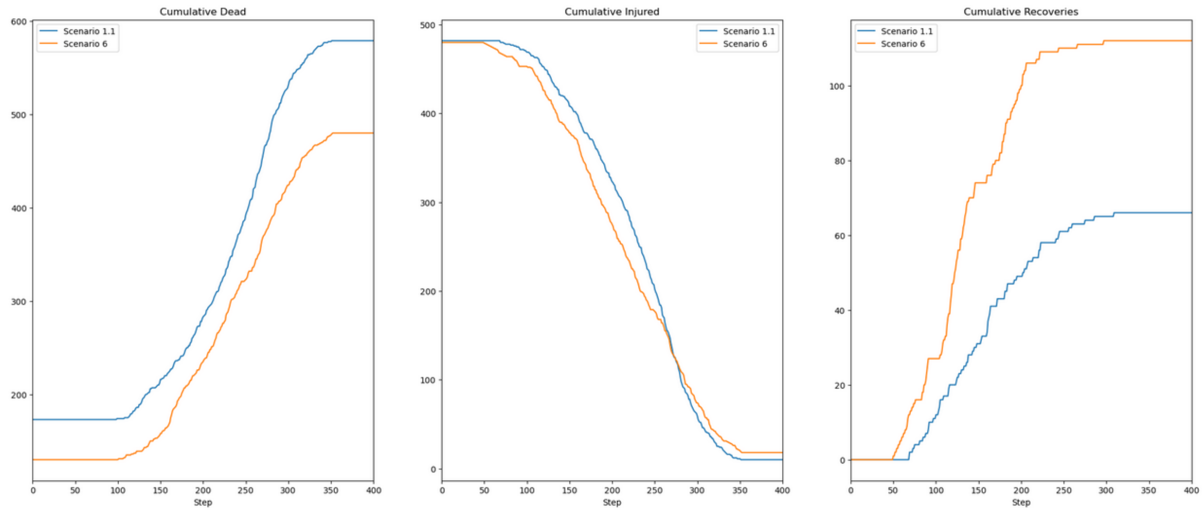


Figure 21: Comparison KPI's of scenario 1.1 and implementation of RMC & helicopter

It could be seen when the policies are applied together there are still the benefits of both. However, the road maintenance cars cannot be so visible due to the short sightedness limitation of the model. The road maintenance cars should make the system much more efficient as the system continues but as all people that are injured die in the model in maximum 360 minutes it is not that visible. The cumulative recoveries therefore cannot be classified as a synthesis effect and could be either of the policies that correspond to such a significant increase.

Scenarios 4, 5 and 6 indicate, and therefore answer the second main research question “What is the influence of implementing road maintenance or trauma helicopters on the effectiveness of rescue operations?” with that there can only be net benefit from introducing trauma helicopters that are much faster than normal ambulances and are not bound by the road situation. It is also a benefit to have road maintenance cars as it makes the road network much more efficient and in extreme cases where there are no nodes that are available to be reached, they will fix the roads to enable ambulances to be able to attend to the injured. Thus, both policies seem to be net positive with respect to the outputs of the model.



7 - Conclusion, Recommendation & Limitations

This section will highlight the major conclusions & recommendations that have been reached through the analysis of the model results. Then it shall also reflect on the limitations of the current model with regards to the setup of the experiments, the capability of the model itself and the conceptual, logic based anomalies that may have caused certain artefacts unexpected in the results. The section concludes with future work and how the current model can be scaled up to answer more research questions.

7.1 Conclusion & Recommendations

In conclusion, the exploratory modelling has shown that the model is quite sensitive to input parameters especially those regarding the probabilities of building material and resident injury / death probabilities. These parameters directly correspond to two additional policy measures which could be increasing the budget on earthquake awareness education and giving more housing permits to those buildings that are built on steel materials.

The second main question, which was primarily concerned with the policy recommendations that were introducing Trauma Helicopters and Road Maintenance Cars, has been given an answer by the output of the models. The answer is that there is only net benefit with regards to the total number of recoveries in the system, which is a critical KPI in earthquake disaster situations.

Bringing all of these together, the model and our team suggests the following;

- Increase budget on Earthquake Awareness Education (High Education Residents)
- Delegate housing permits to those projects with more steel construction
- Delegate budget for Trauma Helicopters & Road Maintenance

7.2. Limitations

The model is a quick and understandable representation of the real case of a disaster response scenario and fulfils the criteria successfully to create a working and analysable model. However, the limitations of the model are extensive when compared to a real life earthquake disaster response scenario as it lacks the nuances that are present in a real life scenario. Some are:

- The model scope does not include the disaster response with regards to other agencies who are financially compensated by the ministry of health and are kept in reserve for disaster response situations.
- The model scope leads to the assumption that the hospitals own the ambulances and that ambulances are kept at the hospitals if they are empty at all times. Although it is true for a number of cases, there are also many ambulances that are kept in hubs especially when places that are quite far from hospitals are concerned.
- The model scope initiates only the “mainshock” of the earthquake and does not think about an “aftershock” earthquake or precursory one which is very common in real life scenarios.

- The initiation of the injury of residents are only handled after the earthquake is initialised and does not consider further injuries that could happen due to walking in hazard terrain etc. later on
- The residents do not have different severity of injuries with respect to recovery time but only severity of injuries with respect to death time. This was the case because the recovery time is a constant that is passed to the model and not a distribution. This makes it so that every resident that gets to the hospital will be cured in the same amount of time.
- The hospitals never get damaged. It could have been a case that a hospital is deemed risky and that due to aftershock risk the operation conditions inside the hospital change.
- There is no panic which causes people to rush to streets that is causing more gridlocks which makes it harder for Ambulances to move through in extreme scenarios.
- The model does not differentiate much between first aid and longer medical care. This corresponds to the fact that, a resident never dies if they are in an ambulance and thus we can conclude that they receive first aid enough so they do not die. However, in the hospital it could be the case that even if there are not enough beds available due to extraordinary circumstances people who are injured less severely cannot be admitted and only applied first aid whereas the people who are severely injured are prioritised. This is not realised in the model.

The reality limitations are also not only due to the nuances of the earthquake disasters but also are caused by:

- The *nodes_data.csv* file contains lengths that are not able to be interpreted as kilometres or metres. The reasoning for this is that Turin becomes a very large place if the assumption is made to be kilometres and very small if it is metres due to how fast ambulances etc. can cover the distance. Thus, there was a trial and error process to scale the model parameters such as speed to get results that sound meaningful and not extreme cases such as an ambulance teleporting next to an injured resident. This of course introduces the bias of the modeller and also the observers. To mitigate this, peer reviewing has been utilised however it is quite hard to neglect the introduced bias when it is a close team who is working on the same goal.
- The road maintenance cars go to the closest node that has broken edges instead of going to the node with most broken edges. This of course makes their run much less efficient due to not having a priority set.
- The helicopter functionality decides which injured person to go to according to the shortest path function and does not use a Euclidean distance. This has the drawbacks if there is no shortest path to a node the helicopter would break. Due to the low number of residents and buildings compared to the scalability of the model, this does not create big problems in the runs. However, the code would not work if there were around 12000 buildings. To fix this, the try and raise exception functions in python should be utilised or the shortest path length should be calculated through a get_euclidean_distance function which we did not have time to fix the bugs for in the allotted time. Thus, due to parameterization this *did not* cause problems, but could with higher numbers.
- The fixed number of total residents of 8000 makes the amount of injuries much lower, although resulting in a lower runtime, it reduces the amount of realism considering there are more than 15000 nodes.

- There is no seed set at the experimentation stage which makes the current .csv files irreplicable.
- All residents die at most at 360 minutes (6 hrs) this means that having the model run for 2880 minutes (2 days) is not necessary. However, this also means that it fails to replicate the realisticness that the disaster response continues until even after 1.5 weeks.
- The implementation of the monitor that counts the number of hospitals that are full was wrong and therefore this is reflected in the csv files. However, it can be seen in validation that the agent logic works correctly.

7.2. Future Work

Future work can build upon the limitations of the model that have been detailed in the previous subsection. There could be more implementation of the earthquake processes such as actually finding the victims of the collapsed buildings. This requires a great deal of effort and would make the model more realistic. The roads that are broken can also have degrees of brokenness. Some roads are usable whereas others would not be preferred by Ambulances. It is quite important to input other agents who interact with the injured residents such as disaster response NGOs. Also, there could be initiation of ad hoc hospitals that are created only to respond to the specific incident. An important monitor can also be added, namely, the finances regarding the ambulances, helicopters etc. All these can build upon and scale the current model that we have delivered.

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Appendices

Appendix A. Conceptual model

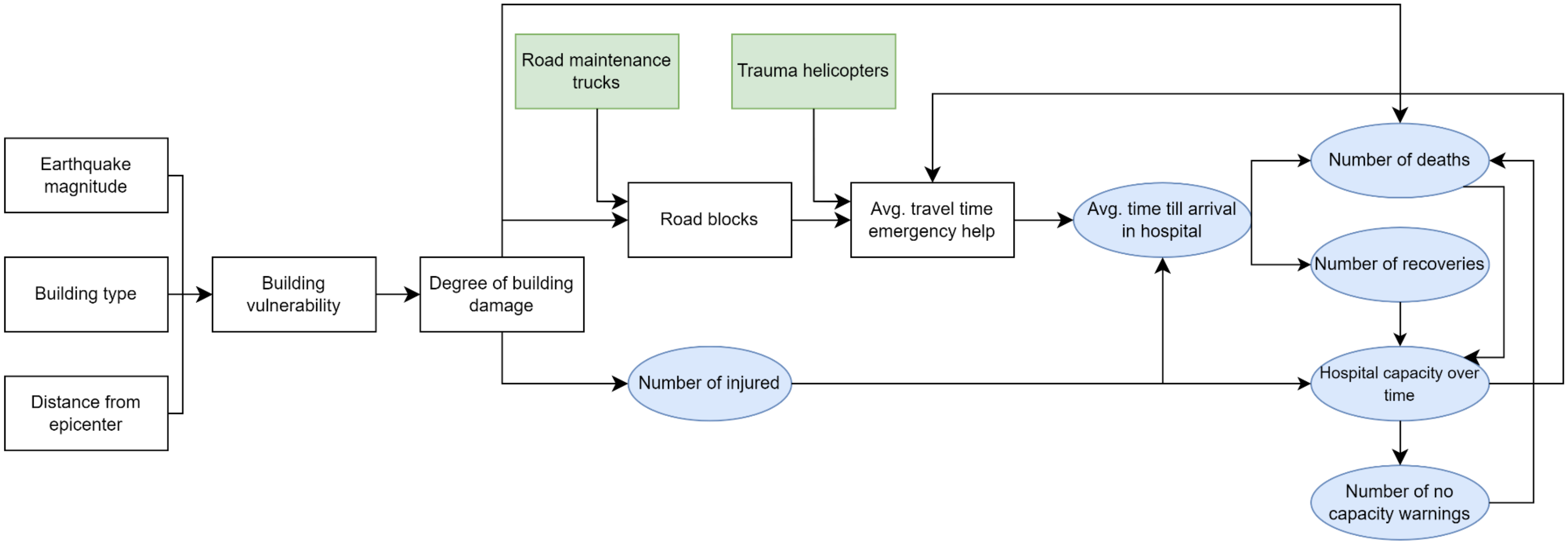

Figure 22: Conceptual model of the system

Conceptual model

Within the model, four different entities exist; residents, buildings, roads and ambulances. Later on, road maintenance trucks and trauma helicopters will be added as policy measures, which are depicted in green. The key performance indicators of the model are depicted in blue.

As was mentioned in the model description, earthquake magnitude, building type and distance from epicentre determine the vulnerability of a building. This, in turn, determines the degree of building damage and the probability to collapse. The degree of building damage determines the number of injured people and deaths. When a building collapses, the roads around that specific building will be blocked due to debris falling off that building. Once a road is closed, the ambulance (or RMC) cannot use it for transportation to the hospital and must find another route to the injured resident and back to the hospital. This will result in longer travel times for ambulances. Each hospital has a maximum capacity, which will be represented by a limited number of beds. Ambulances will leave from the hospital to the nearest victim and they will bring the person back to the same hospital. This will continue until there are no injured residents left. When a hospital has reached its maximum capacity, the ambulance cannot leave and the injured resident it was supposed to pick up, will die. In the model, we will count the number of times it occurs that ambulances cannot leave due to no capacity. When it takes too long to be picked up by an ambulance, an injured resident will also die. After spending a certain amount of time in the hospital, injured people will recover.

Road Maintenance Workers and helicopters can also be introduced to the model. The RMCs will repair the broken roads. This will make the roads available again for the ambulances, and could consequently therefore reduce the travel time to an injured resident. Helicopters can fly from a hospital to an injured resident and fly back to the nearest hospital. This could lower the travel time of emergency help.

Appendix B. Parameters model

Table 5: Experimental and fixed parameters of the model

Experimental parameter	**Unit**	**Value**
Probability of resident getting injured when building has collapsed	[%]	0, …, 100
Probability of resident dying when building has collapsed	[%]	0, …, 100
Probability of resident getting injured when building has a high amount of damage	[%]	0, …, 100
Probability of resident dying when building has a high amount of damage	[%]	0, …, 100
*Probability of a building being steel**	[%]	0, …, 100
Earthquake magnitude	Richter scale	0, .., 10
Fixed parameters	**Unit**	**Value**
Number of buildings	[-]	400
Number of residents per building	[-]	20
Number of hospitals	[-]	20
Number of ambulances per hospital	[-]	1
Number of RMC HQs	[-]	1
Number of RMCs per HQ	[-]	1
Number of Helicopter HQs	[-]	1
Number of Helicopters per HQ	[-]	1
Time until injured to death	[minutes]	triangular(90, 360, 270)
Recovery time	[minutes]	45
Speed Ambulance	[metres/minute]	90
Speed RMC	[metres/minute]	60
Speed Helicopter	[metres/minute]	450
Capacity Hospitals	[beds]	10
Capacity Ambulance	[seats]	1
Capacity Helicopter	[seats]	1

Time to fix one road (RMC)	minutes	60
Probability of a road closing when a building has collapsed	[%]	80
Probability of a road closing when a building has collapsed	[%]	50
*Probability size building***	[%]	⅓

*The probabilities of ‘brick’ and ‘concrete’ will both be the remaining value of the probability of steel divided by two.
**The probability of the size of the buildings is equal for ‘short’, ‘medium’, ‘tall’.

Argumentation of the Fixed Parameters

There are a few parameters that are run each time that a model runs. These fixed parameters have been constructed due to the scope of the model that has been fixed due to time constraints. A list of these fixed parameters can be found under Appendix B. Please note that the main assumption of the project is that the aim is to build *a model* and interpret its results and not necessarily create the most realistic earthquake simulation. The explanations for each can be found below:

Number of Buildings, Number of Residents per Building: Has been selected to be 400 and 20 respectively. The reason for this is not to make the model big as residents get created in each building. Thus, with 20 residents per building it increases the total number of residents to be 8000. This has direct consequences with the amount of people that are injured as residents get injured based on a certain probability. With a higher number of injured, due to checking the status of the residents, the model had to be run for a longer time. This however, was not an option due to lack of time as stated in the limitations.

Number of Hospitals: 20 has been selected as the project description file stated that the city of Turin has about 20 hospitals.

Number of Ambulances per Hospital: This has been denoted as 1 as currently according to statistics Netherlands currently has 725 ambulances that are available 24/7 (Nivel, 2013) . Considering the total number of hospitals in the Netherlands which was 618 (Michas, 2022). This corresponds to a basic estimate of ~1 ambulance per hospital. It is however true that there are nuances to this in the real world. Not all deployed hospitals belong to a hospital and are sometimes deployed by subcontractors who are financed by the ministry of health. However, the reader must recognize that such nuances are quite complex and require more time and more effort in thinking who these sub-contractors are and how they work etc.

Number of Road Maintenance Car HQs, Road Maintenance Cars, Helicopter HQs and Helicopters per HQ: All values have been considered to be 1 as the policy switches are designed to introduce an external support to the system. This means that the expectation of the results when these policies are present can be seen explicitly even if their numbers are not so high. To not convolute the model, and also that it would not introduce more insight to our analysis their number has been set to the lowest possible.

Time from injured to death*:* The time it takes for a resident to reach from an injured status to death was assumed to be a triangular distribution that took values between 90 and 360, thus 1.5 hrs and 6 hrs. The values have been determined to be closer to 360 then 90. The reason for a random distribution is quite simple. In reality, it is expected that the severity of the injuries that people suffer will vary. This variation will in turn lead to people having either less or more time to wait until being rescued. The triangular distribution thus, achieves this. The values of 90 and 360 minutes on the other hand has been determined with respect to brainstorming as in literature there are a lot of injuries and times stated that conflict with each other, making it hard to select a baseline.

Recovery Time: The time that it take to recovery has been set with respect to the scope of the model and how the output is. This was done because in some cases the recovery time was extremely high and in some low. Through trial and error we have agreed on a time that is good enough to flush the residents who are currently in the hospitals out of the system.

Speed Ambulance: The speed of the ambulance moves 90 m/minute and is in no way correlated with its real counterpart. The reasoning for this is quite simple as the lengths that were given in the *coord_full.csv* average to about 65. This means that due to the logic in our ambulances, if the speed is higher than the length itself it would only move in 1 tick whereas if the speed is lower than the length it would wait until the total length is covered with respect to multiples of the speed. The main mathematical function that is used for implementing speed for the ambulances road maintenance cars and helicopters is as follows:

Time to wait on node = length // speed

Quite simple, but effective. This makes the speed implementation easy and the agents perform with real life representations (but scaled down) going from one node to another.

Speed RMC & Helicopter: These follow the assumption and logic of the ambulances. A critical thing to note is that RMCs are a bit slower, 60 m/metres as the average length had been found out to be 65. Therefore our aim was to make it so that an RMC takes more time moving from node to node. For Helicopters the opposite is true. They are about 5x faster than ambulances and can move 450 m/minute. They also are not limited by roads which makes it quite a fast jump between nodes which is quite expected.

Capacity Hospitals, Ambulance, Helicopter: The hospital capacity has been created with respect to trial and error and has been set as 10. The reasoning was to create a dynamic where there would be way more injuries then the hospitals can allow for only in Turin. This was due to the understanding that normally when there are natural disasters it is quite common that people are sent to hospitals in other cities/regions as the local hospitals cannot keep up with the demand. Ambulance capacity has been set as 1. The reasoning for this is because in most Ambulances there is one dedicated stretcher for a person and only in big emergencies they allow 2 people on the back. The other couch is reserved for the medical professional. For the helicopter the capacity has been determined as the same as ambulances.

Probability Size Building: Because our research questions did not delve to the size of the buildings and their implications on collapsing or damages we decided to let the probability be ⅓ while initializing buildings. They also did not have an impact on the vulnerability calculations.

Appendix C. Formalisation

C1 Graph of Turin

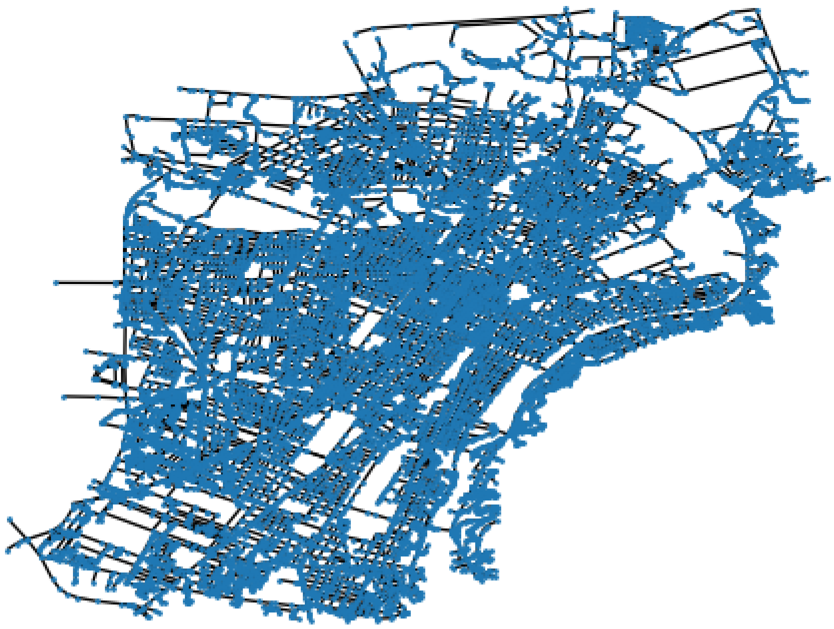

Figure 23: Graph/grid of the model of Turin

The city of Turin is represented by a graph with nodes and edges. The links represent roads and nodes are the intersections of roads. This graph was generated with python using the Networkx library. The csv files ‘coord_full’ and ‘nodes_data’ were used to generate this graph. These files were provided to us by the course coordinator.

C2 Initialisation model

Pseudo code model setup

Model class

Attributes

```
-Dictionaries of the residents, hospitals and roads in the model (to
keep track of them)
-Scenario parameters
-Policy intervention parameters
-Data collection

Earthquake is initialised as a node on 0,0 (This is done first to
make further coding more easy and concise)
```

Initialisation Hospital and Ambulances

```
Create a number of hospitals with a unique ID, and give them a random
node as location (as long as no other hospital is located on that
node).
```

```
For each hospital:
      Create a number of ambulances with a unique ID on the same
      location of the hospital.
```

<u>Initialisation Buildings and Residents</u>

```
Create a number of  Buildings with a unique ID, and give them a
random node as location (as long as no other hospital/building is
located on that node).

For each building:
      -Determine the building damage
      -Create a number of Residents with a unique ID on the same
      location of the respective Building.

      For each Resident:
            Determine if they are have become injured or dead due to
            the earthquake
```

<u>Initialisation RMC</u>

```
Create a number of Road maintenance HQs, and give them a random node
as location (as long as no other building etc is located on that
node).

For each HQ:
      -Create a number of Road Maintenance Cars (RMC) with a unique
      ID on the same location as the HQ.
```

<u>Initialisation Helicopters</u>

```
Create a number of Helicopter HQs, and give them a random node as
location (as long as no other building etc is located on that node).

For each HQ:
      -Create a number of helicopters with a unique ID on the same
      location as the HQ.
```

C3 Buildings getting damaged

To determine the amount of damage a building suffers (the damage status), damage probabilities are determined:

➢ Building Damage Probability distribution:

- $CollapseProbabilityCP$ = 0.7 × VM + 0.1
- $HighdamageProbabilityHP$ = −0.15 × VM + 0.3
- $NoDamageProbabilityNP$ = −0.55 × VM + 0.6

The summation of these three probabilities is equal to 1. By using these probabilities and by drawing a number between 0 and 1, the Building damage will be determined. The value of a probability depends on how vulnerable a building is to an earthquake (*VM*). Having a high vulnerability maximizes the chance of the building getting damaged, and a low vulnerability minimizes it. The Building vulnerability factor will have a value between the 0 and the 1. Below the formula and the steps to determine the Building vulnerability are given.

Building Vulnerability VM:
$VM = TM \times HM \times DM \times EM$

Several factors contribute to the degree of building vulnerability: *Building Type* (TM), *Building Height* (HM), *Distance from the epicenter* (DM), *Earthquake intensity* (EM). These multipliers can take a value between 0 and 1, with 0 minimizing the chance of building damage and 1 maximizing it.

➢ Building Type Multiplier TM:
• Steel building: TM=0.0
• Concrete building: TM=0.5
• Brick building: TM=1.0

➢ Building Height Multiplier HM:
• Tall building: HM=1.0
• Medium-height building: HM=0.6
• Short building: HM=0.2

➢ Distance from epicenter Multiplier DM:
• DM= $(Maxdistance - Distance)$ / $(Maxdisatnce - Mindistance)$
Max distance: the distance between the epicenter and the farthest building
Min distance: the distance between the epicenter and the closest building
Distance: the distance between the epicenter and the considered building

The factor of the distance from the epicenter of the considered building is relativised by the maximal and minimal distance a building has to the epicenter.

➢ Earthquake intensity multiplier EM:
• Weak earthquake: EM=0.2
• Strong earthquake: EM=0.5
• Major earthquake: EM = 0.7
• Severe earthquake: EM = 1.0

Appendix D. Experiments

Table 6: Parameter values of scenarios

	resident_injured_prob_collapse	resident_death_prob_collapse	resident_injured_prob_highdam	resident_death_prob_highdam	building_material_steel_prob	Earthquake magnitude	Code:
Scenario 1 (High Ed High Steel Base Case)	**0.6**	**0.2**	**0.2**	**0.1**	**0.8**	**0.2 (Low EM)**	**1.1**
	0.6	0.2	0.2	0.1	0.8	0.8 (High EM)	1.2
Scenario 2 (High Ed Low Steel)	0.6	0.2	0.2	0.1	0.4	0.2 (Low EM)	2.1
	0.6	0.2	0.2	0.1	0.4	0.8 (High EM)	2.2
Scenario 3 (Low Ed High Steel)	0.3	0.5	0.5	0.2	0.8	0.2 (Low EM)	3.1
	0.3	0.5	0.5	0.2	0.8	0.8 (High EM)	3.2
Policy Scenario 1 (Base case + RoadM)	0.6	0.2	0.2	0.1	0.8	0.2 (Low EM)	4
Policy Scenario 2 (Base Case+Helicopter)	0.6	0.2	0.2	0.1	0.8	0.2 (Low EM)	5
Both Policies (Both Case + Basel)	0.6	0.2	0.2	0.1	0.8	0.2 (Low EM)	6

Appendix E. Individual Scenario Descriptions

Scenario 1.1

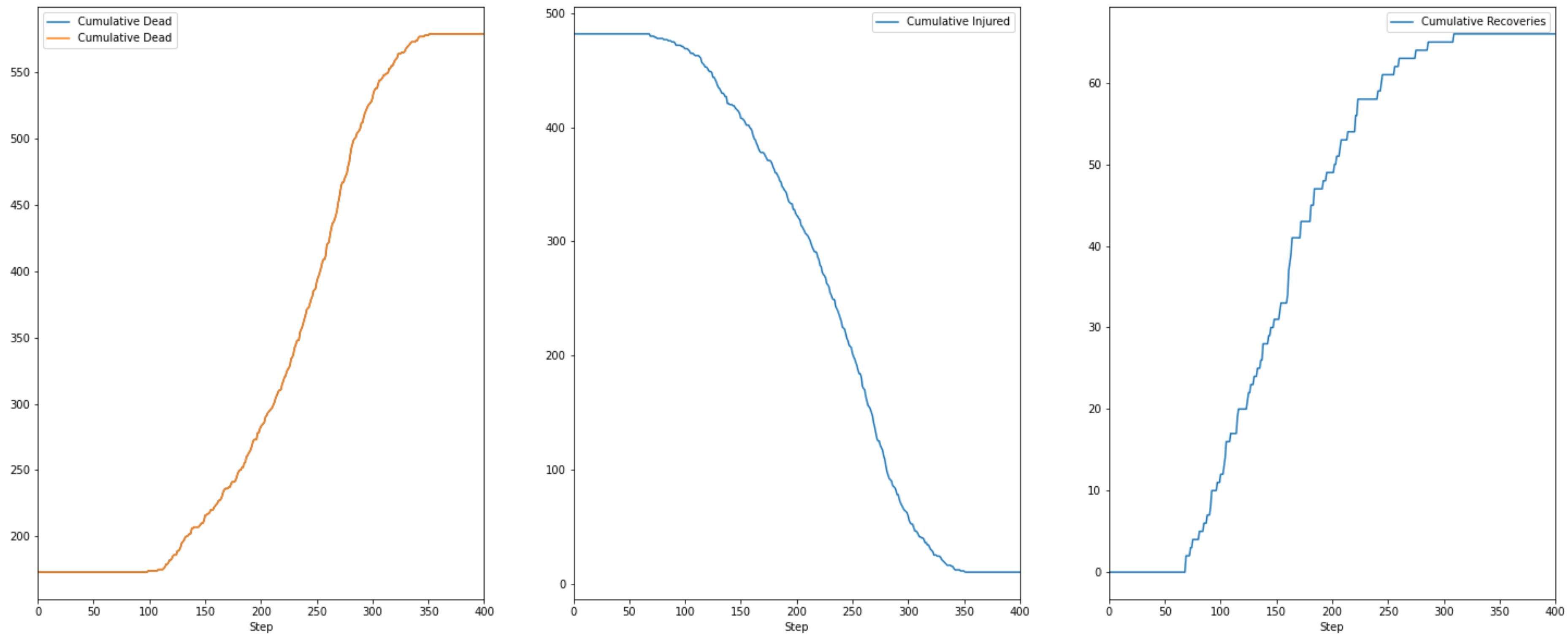

Figure 24: KPI results scenario 1.1

In this scenario the education of the residents regarding earthquake protection is high, the buildings are proportionally higher in steel and the earthquake magnitude is low. This case is also denoted the base case and is the primary comparison for other scenarios. This specific replication starts with a total of 173 dead and the numbers rise to 579. In the first moments after the earthquake there are 482 injured people where this number diminishes in time as they either die or are recovered. The total number of recoveries rise to 66 near the end of the model.

Scenario 1.2

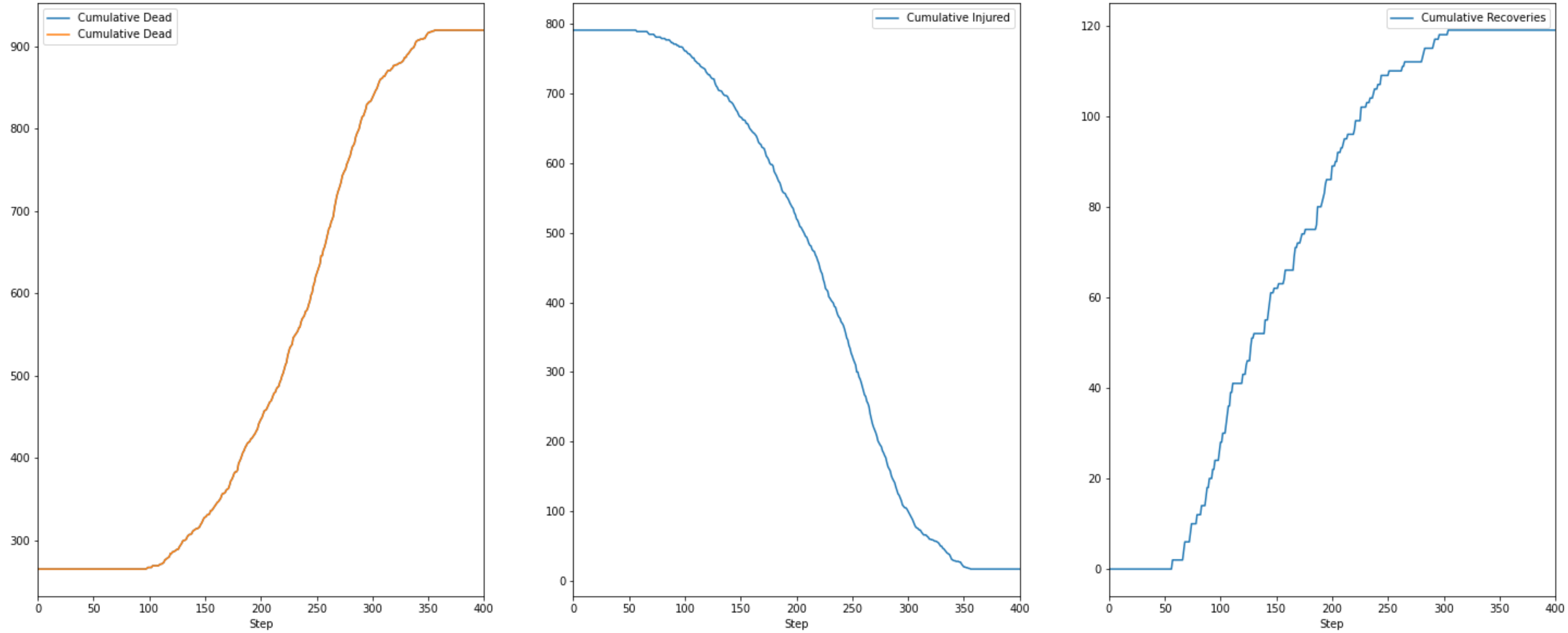

Figure 25: KPI results scenario 1.2

In scenario 1.2 there was a high education level, high probability of steel and high value for the magnitude of the earthquake. The most left diagram shows that 265 residents die right after the earthquake, and after approximately 3 hours everyone who is still injured dies. The second diagram shows that after 3 hours roughly 800 residents are not injured anymore, due to dying or recovering. In total 120 people have recovered, meaning that roughly 690 people still died. In the last diagram you can see that only for a short period of time the hospitals were at max capacity.

Appendix E. Individual Scenario Descriptions (continued)

Scenario 2.1

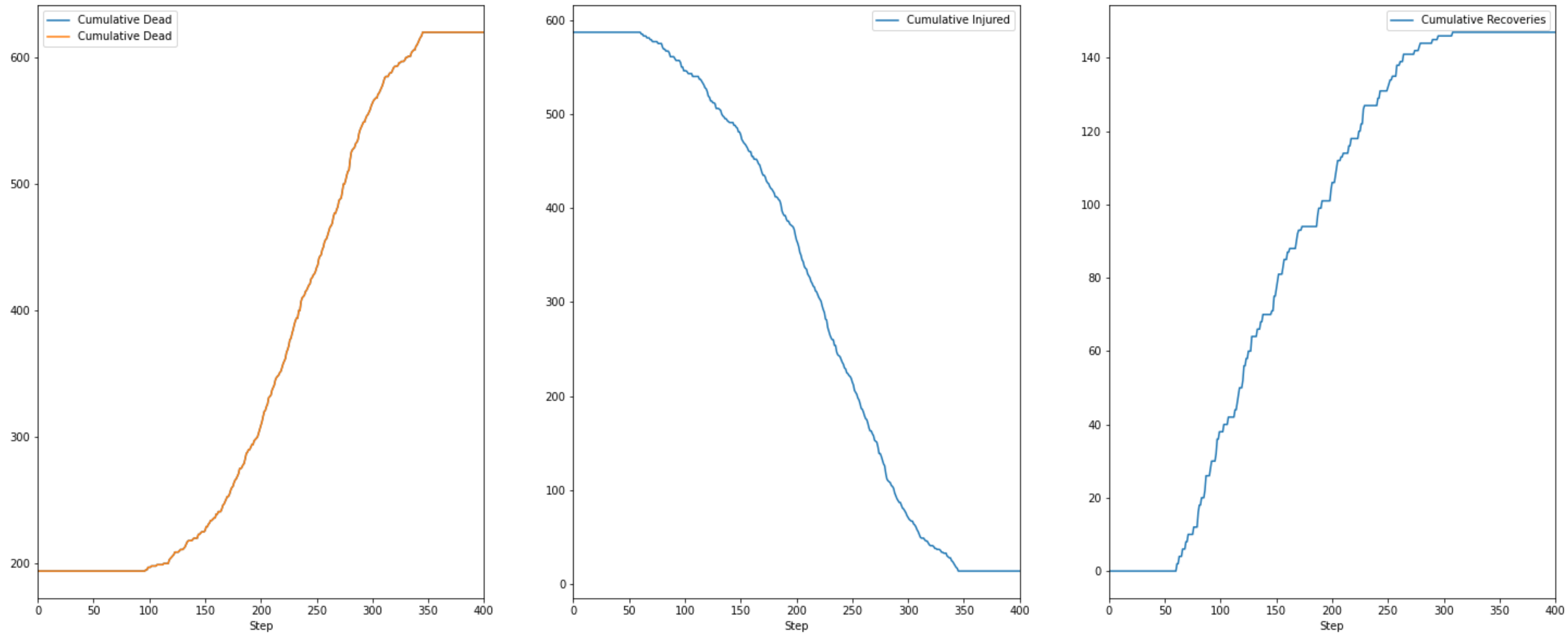

Figure 26: KPI results scenario 2.1

In this scenario our setup notes that there is high awareness (education) against earthquakes of the residents, and that there is a lower amount of steel buildings in the system. The earthquake magnitude is low. The statistics on this specific replication are that the number of dead people right after the earthquake is 194 and it increases steadily until 620. The number of injured people starts from 587 and goes down until the end of the steps. Cumulative recoveries go up to 147 and there are no hospitals full throughout the run.

Scenario 2.2

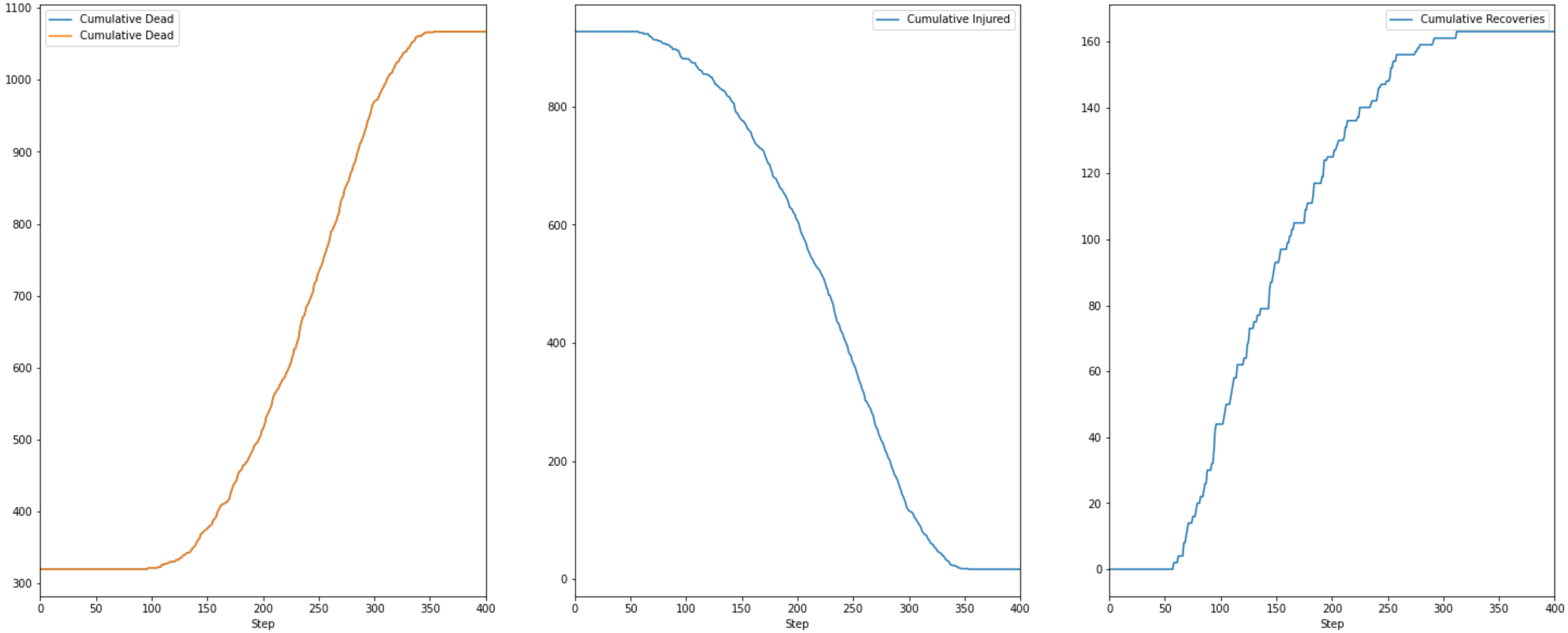

Figure 27: KPI results scenario 2.2

Scenario 2.2 consists of residents who are more prepared against earthquakes (higher education) and the model has a lower proportion of steel buildings. The earthquake magnitude is high. In the first steps after the earthquake expectedly there are a high amount of deaths (compared to the base case) resulting in 320 dead people. This number increases to 1067 as the vast number of injured people are not able to be carried into hospitals in time as there isn't enough capacity currently in the model. 200 beds are not enough for this case. The cumulative recovery is 163 in the end.

Scenario 3.1

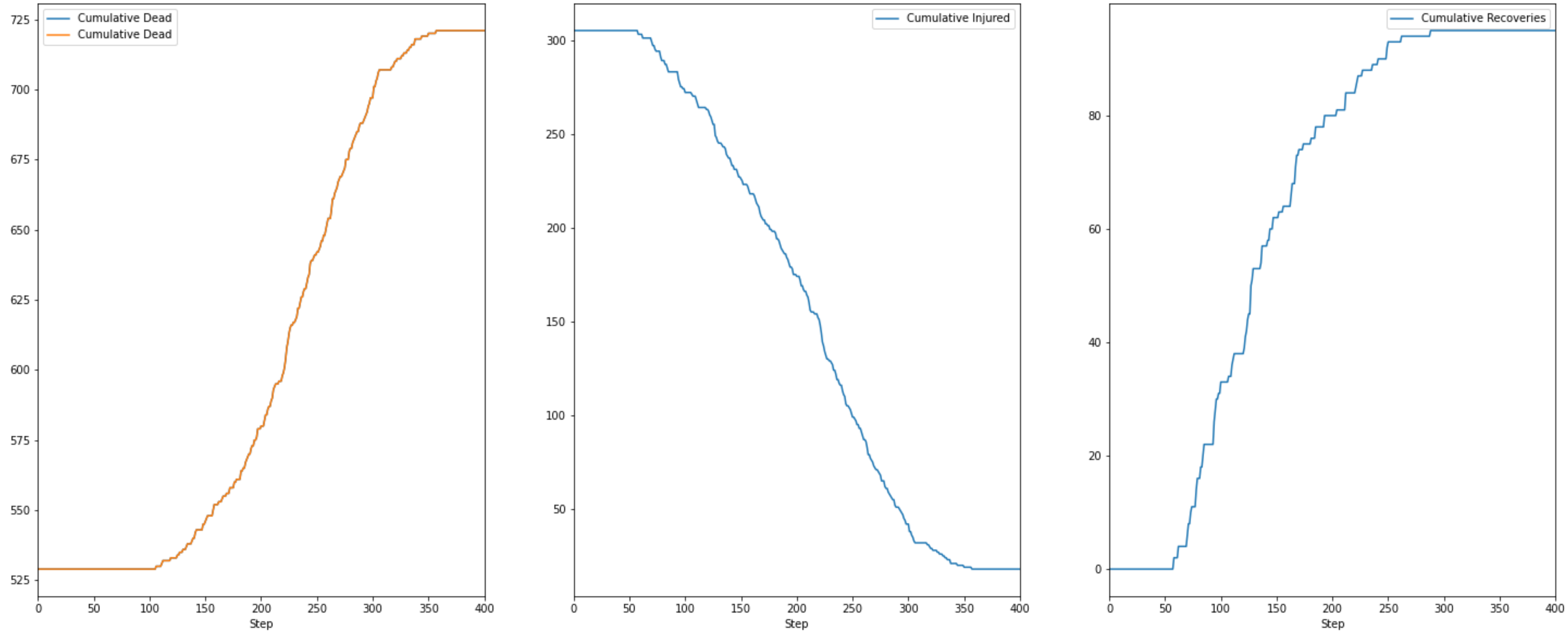

Figure 28: KPI results scenario 3.1

Scenario 3.1 has residents who have low education against disaster preparedness and the model starts with a higher proportion of steel buildings. The earthquake magnitude is low. The number of dead right after the earthquake started from 529 and rose to 721. Injured numbers start from 305 then reduce in number as time goes on. The cumulative recoveries go to 95.

Appendix E. Individual Scenario Descriptions (continued)

Scenario 3.2

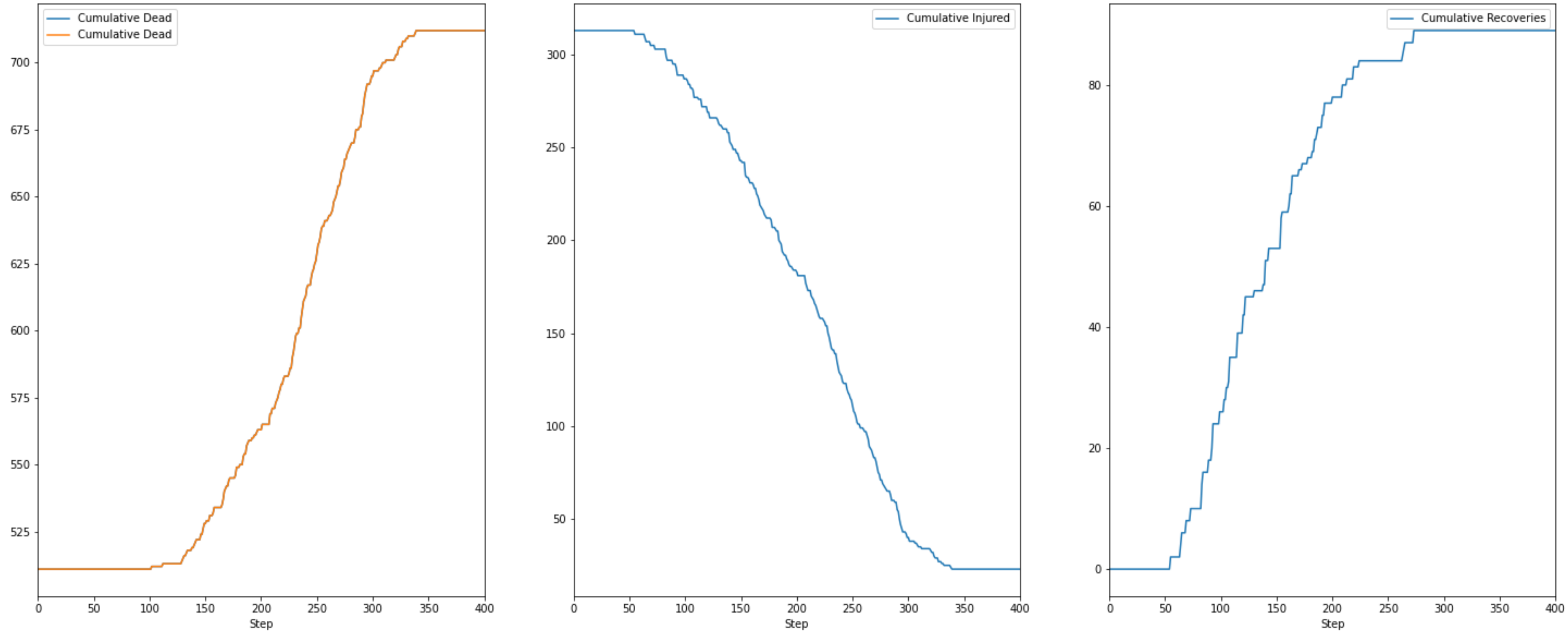

Figure 29: : KPI results scenario 3.2

For scenarios the residents have a low education level, the probability of a building being made of steel has a high value, and the magnitude of the earthquake also has a high. The cumulative death starts in this scenario at 511 and ends with 712. The amount of injured residents after the earthquake amount to a total of 313. At the end of the model 89 people had recovered.