Challenge 2: Surviving the zombie apocalypse

MORENO Tatiana[1,2], CARREÑO Diego[1,3], and MEJIA Johan[1,4]

[1]MSc. IT: Data Science
[3]diego-andres.carreno-avila@imt-atlantique.net
[2]jenny-tatiana.moreno-perea@imt-atlantique.net
[4]johan-steven.mejia-mogollon@imt-atlantique.net
[1]IMT ATLANTIQUE

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1 Context

In 2019 a strange virus was detected in the city of Rize, Turkey, in which dead people came back to life hours after their death. These people present violent behavior, attack only humans and do not present any apparent reasoning. The last living human in the city of Rize was recorded on August 18, 2019.

1.1 How to save the world ?

The **European Union** (EU) has limited troops and will have unlimited nuclear bombs to counter the zombie attack and the spread of the virus.

Following the status report delivered on August 18, 2018 where it was reported that the entire Rize population was infected, the EU decided to deploy 20 military troops to contain the epidemic which will be ready within 2 months of the first global report of the virus status. The soldiers will be trained to protect the surviving population of the area to which they will be assigned, as well as to prevent the arrival of more zombies in the area.

If the emergency measures do not completely stop the invasion, the EU would be ready to bombard the European continent with nuclear bombs 4 months after the beginning of the epidemic, eradicating all forms of life (except for salamanders) where the bomb will hit. The after-effects of the radiation would not allow any organism to transit the area again. The drastic measures would be executed in order to save as many survivors as possible.

The EU has contracted us to model the pandemic and help the government stop the spread of the virus. Our team is relocated to a bunker in Brest city in order to isolate the experts and give us time to study how to save the world. Our task is identify the zones where the virus spreads faster and generates a zombie outbreak that spreads rapidly to adjacent cities and towns, causing the number of infected to increase disproportionately.

1.2 What is known

Although some information on zombie behavior has been obtained, there is no knowledge of *how many exist, where they are found and how do they evolve*. Therefore this information must be estimated. More however, some information managed to be leaked before the devastation of the entire city. Among the available information we have:

1. They only kill humans: they have a very acute sense of smell, thanks to the human pheromones they can detect the presence of humans up to 30km away. It is easy for them to detect humans communities, so they look for areas where there is a greater number of humans present
2. They are not much stronger than humans: although they have the ability to track they have a strength very similar to that of a human of an average age of 30 years and are not immune to lethal weapons for an average human (firearms, knives, etc)
3. Bad for climbing: Although they have strong arms and legs, their articulations do not respond correctly, which makes it difficult for them to climb, they avoid moving to places with an inclination of more than 10 degrees approximately. Therefore, they preferred to move in places where there is no slope (degree 0) or it is downhill (negative slope).
4. The zombies move at night: they eat and infect the population they encounter in the morning hours and cease activities in the afternoon, a period that the survivors take advantage of to annihilate as many zombies as possible.
5. They have a limited lifespan: the virus survives in the body for up to 15 days after conversion to zombie.
6. Non-swimming: since humans do not persist in water, they avoid lakes, rivers, sea, etc.

2 Methodology

The problematic follows a model of a zombie infection, wherein the infection spreads rapidly among the human population converting them to zombies in the process. We use networks as the topology and allow our human and zombies agents to act on and change this topology. Additionally, we take a dynamic **Suceptible - Infected - Recovered** (`SIR`) as referential propagation model, with three possible scenarios:

1. Humans are susceptible to becoming zombies.
2. Zombies can die.
3. Dead people cannot revive.

As a first objective we must capture the population density and the elevation from images and translate them into a graph network, this will be done in order to determine the number of infected humans and how will be the behavior of the zombies to move from cell to cell. This will allow us to make a model of virus propagation based on the theory of epidemics in graphs.

For this purpose, the international census center has provided us with a map of the population of inhabitants in Europe before the virus existed, i.e. around the end of 2018 and the elevation map since, as mentioned above, they are bad for climbing. At that time, the European continent had a population density shown in the map in the Figure 1a, where each pixel represents a population density between $[0, 3000]$ **inhabitants per Km^2** (in/Km^2), where white color represent the maximum population density and black the minimum.

(a) (b)

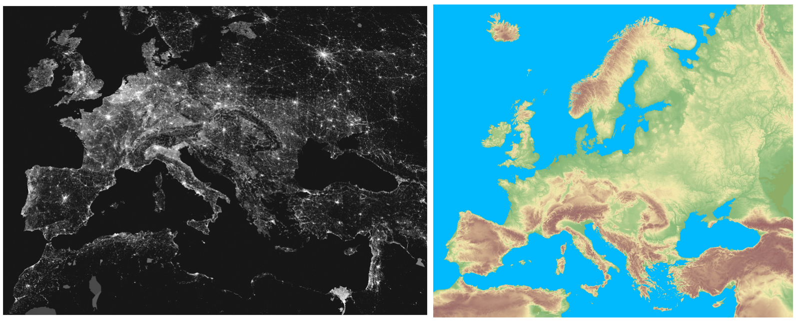

Figure 1: Maps with the description of (a) initial population density expressed in grayscale on August 18, 2019 and (b) elevation of the terrain where the apocalypse takes place.

Then it is important to develop a model to predict the spread of the virus, in order to estimate the best places to put the troops, keeping in mind that the scientists are in the city of Brest and that we need time to perform our calculations.

Finally, in order to save the world, it is necessary to find points to put bombs where it will be possible to annihilate as many zombies as possible without suffering too many human losses, and to ensure the survival of mankind.

3 Geographic and population modeling

As mentioned earlier in the to save the world, our team is located in a bunker in the city of Brest and has information on population maps prior to the report of the last living person in Rinze and ground elevation for the year 2018 as shown in Section 2. In order to create the graph that will allow us to represent the spread of the virus, a statistical analysis and a pre-processing of the data will be done.

3.1 Data understanding and pre-processing

Each map is in BMP format, where each pixel represents 1 Km^2. However, each map has different characteristics, so initially a separate analysis is performed.

3.1.1 Population map

According to the information provided, the population density file has a red pixel for the center of Rize and a green pixel for the center of Brest, all other pixels are black and white. Maximum density (absolute white color) is 3000 in/Km^2. It has a size of 4830 x 3510 pixels, and 32 different colors.

Figure 2a presents the histogram of colors in density population map, where is observed that there is a large amount of black, which indicates the low probability of humans present. However, 91189 pixel of complete white color was observed, in other words where there are $91189 \times 3000 \approx 274 \times 10^6$ inhabitants that can help to prevent the spread and fight against zombies.

After obtaining the location of the center of Brest and Rize, thanks to the unique colors they present, a complete conversion of the image to grayscale is performed with values between 0 and 255, where 255 is white (more population) and 0 is black (less population). With these values it is possible to calculate the population density per pixel, see Figure 2b

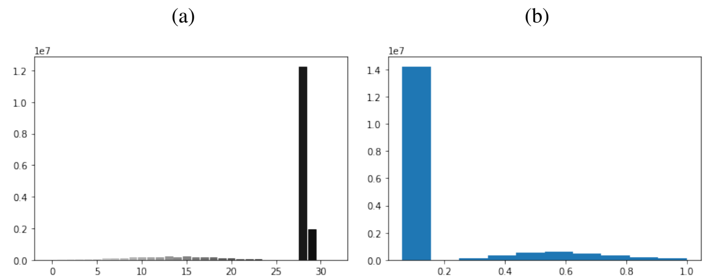

Figure 2: Maps with the description of (a) Color distribution of the original population map and (b) population density distribution after conversion.

With this information we have a population density of 894 in/Km^2 in the center of Brest and 1765 in/Km^2 in the center of Rinze.

3.1.2 Elevation map

The elevation map has a dimension of 4901 x 4251 pixels, where each pixel represents a square kilometer, it has 189 different colors being these tones between blue, yellow, green and red. The Figure 3 represents the histogram obtained, it can be seen that the most present color is blue, representing the sea.

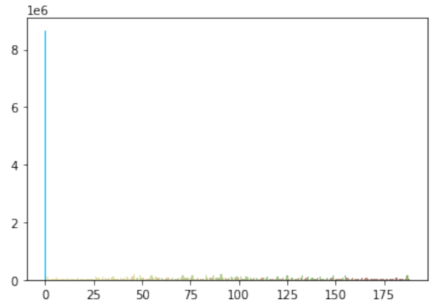

Figure 3: Color distribution on elevation map

In order to facilitate the handling of the map, we tried to reduce the color dimension from three (RGB) to one, i.e. black and white, where 255 (white) will correspond to the highest point at sea level and 0 (black) will correspond to the sea level itself. We known that the highest point is the Mont Blanc which is approximately 4809 m, in the map this point is represented by the darkest brown.

One way to obtain this representation is to make use of the HSV (hue, saturation, value) representation. The Hue dimension can take values between 0 and 360 (see Figure 4a), taking this dimension and representing it in grayscale it is possible to obtain the image shown in Figure 4b, this second image has values between 0 and 138, being 0 red (highest point) and 138 blue (sea).

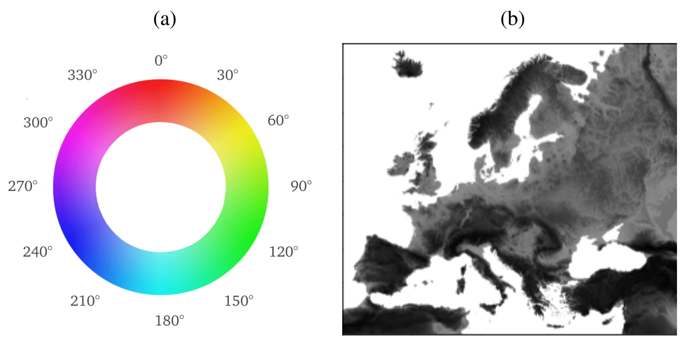

Figure 4: Convertion map from RGB to HSV (a) Hue wheel colors and [1] (b) Color distribution on elevation map

For ease of visualization and calculations, this range is linearly modified to 0 to 255 where 0 corresponds to the sea (lowest point, black) and 255 to Mont Blanc (highest point, white), the resulting image is shown in Figure 5a. In this way the elevation density in each pixel is calculated taking values from 0 to 1 as shown in Figure 5b

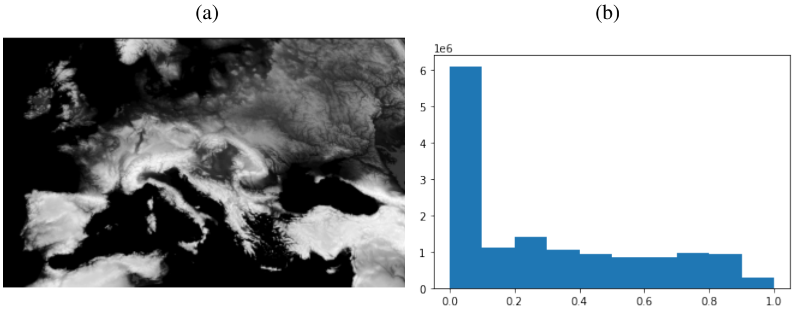

Figure 5: Map obtained in grayscale (a) Elevation map in black and white colors, black lowest point and white high points and (b) elevation density distribution after conversion

In this way it is possible to know the approximate height of an area of 1 Km^2 represented by each pixel, which can be very useful considering that zombies are bad at climbing and prefer to move to flat areas or areas with negative slopes.

Although in general both maps represent information of very similar areas, precise information about the population density in a square kilometer (one pixel) and the estimated height that this area has with respect to the sea is required, in order to build a model more adapted to reality. The maps present different satellite views and different sizes, it is required to normalize this information.

Thanks to an exhaustive analysis of the maps, we were able to locate 20 points on the coast of Europe and their respective location on each map, as shown in Figure 6.

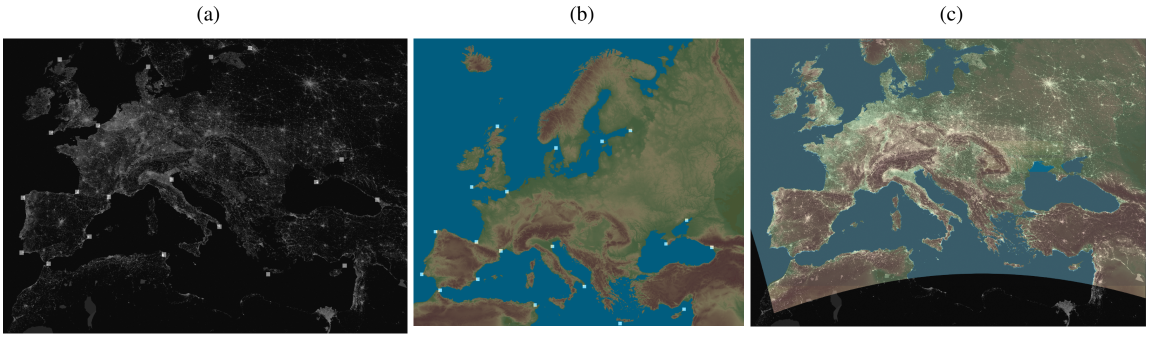

Figure 6: Reference points on each map (a) Reference points on population map (b) Reference points on elevation map. (c) Population and elevation map superposed

The aim is to superimpose the maps in such a way that each pixel represents the same area in each map. This process is performed thanks to the methodology of Infer geometric transformation from control point pairs, making use of polynomial transformations [2]. The result of this process is an elevation map in which the location of zones (pixels) corresponds to the same location on the population map, so for example it is possible to know that in the center of Brest located at coordinates (1306, 669) there is a population density of 894 in/Km^2 and an elevation density of 0.1 approximately.

With this information of the spatial difference of the maps corrected, having the population density and elevation, it is possible to plot the graph, which will allow us to make the prediction of the spread of zombies.

4 Graph construction

According to information on zombie behavior, they have a keen sense of smell that allows them to perceive people up to approximately 30 Km away, they are also known to be bad at climbing and prefer flat areas or negative slopes.

With this information the network will be constructed:

- Vertices: each vertex will be comprised by an area of 15 Km * 15 Km (1 pixel = 1 Km^2), considering that they only move at night, it is estimated that they can reach up to 15 Km and from there consider their next direction, depending on where more humans persist and where it is easier for them to move.
- Attributes: Each vertex will be composed of three attributes:
  1. Node id: Unique ID to identify each zone of 225 Km^2
  2. Human population: Estimate how many humans exist in each cell, who may be able to help fight the zombies or require assistance

3. Zombie population: Estimate the number of zombies present in an area and be able to estimate the radius between infected and non-infected, in addition to identifying how the virus is spreading in Europe

- Edges: Represents every possible movement of the zombie, the weight will represent the facility of a zombie to move between cells.

4.1 Images pre-processing

According to the above, a directional graph is required because it is possible that in one direction there is a high positive slope for the displacement from zone x to zone y, which indicates that zombies would avoid going to y from x, but a negative slope from y to x, where there would be a preference for zombies.

From the final images obtained by map, there are extracted m x n matrices with the population density and the estimated height of each pixel (1 Km^2 representation). With m = 3000 and n = 4830. In order to extract each node (or cell) of the graph, which represents an area of 225 Km^2, the mathematical operation of 2D convolution is used [3]. They are based on the idea of using a kernel and iterating through an input image to create an output image [4]. The size of the output image is given by:

$$n_{\text{out}} = \left\lfloor \frac{n_{\text{in}} + 2p - k}{s} \right\rfloor + 1 \tag{1}$$

Where n_{in} is the number of input features, n_{out} is the number of output features, k is the kernel size , p padding size and s stride size.

For our problem we made use of a 15 x 15 kernel with 1/225 values at all positions in order to obtain at the end the average population density and average altitude in an area of 225 Km^2 (15 Km x 15 Km). Applying Equation 1 for $n_{\text{in}} = [3000, 4830]$, $k = [15, 15]$, $p = [0]$, $s = 15$, it is obtained a $n_{\text{out}} = [200, 322]$. This grid of cells is used as the basis for establishing the connections between zones, in other words edges.

Taking into account the sense of smell of zombies, it is considered that a zombie located in zone (i, j) can perceive humans in 8 directions. Figure 7a shows an example. If the zombie is located in cell (1,1), it could perceive humans in all the cells around it, and wish to move in these directions. Its movement will depend on the difference in altitude between the source node and the destination node, represented as a weight on the edges. As mentioned above, the network is directive.

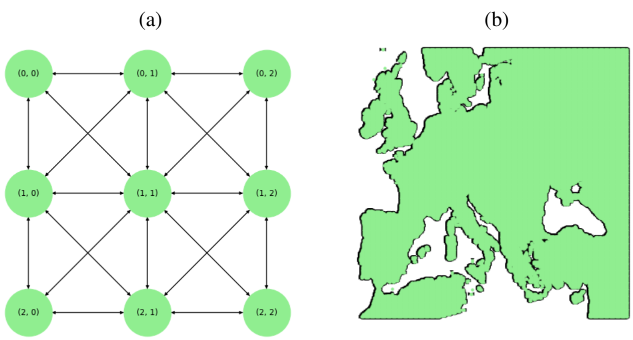

Figure 7: (a) Possible zombie movements and representation of each group of cells in the (a) final generated grid map.

The definition of the piecewise function $f(\theta_{i,j})$ (Equation 2) is made to determine the edge weight (V_i, V_j) for a given difference angle $\theta_{i,j}$ between them.

$$f(\theta_{i,j}) = \begin{cases} 1 & \theta_{i,j} \leq 0, \\ 1 - \dfrac{\theta_{i,j}}{10} & 0 < \theta_{i,j} \leq 10, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

As zombies do not swim and people who might arrive on cruise ships or boats are not in danger, this zone is omitted from the graph in order to simplify the analysis.

The Figure 7b shows the graph obtained. Finally, the last living person in Rinze was reported on August 18, 2019, this date is considered as the beginning of the pandemic and the entire population of humans in Rinze at this date as zombies.

5 Definition of the epidemic propagation model

After having modeled the geographic space as a network, with the definition of the nodes, their attributes and connections, we will show the interaction dynamics between nodes, which will be defined with human/zombie population as attributes on each node.

5.1 Description of the spreading dynamics

To describe the dynamics of epidemic spread, take $H_j(c_i)$ to be the population of humans and $Z_j(c_i)$ the population of zombies in node c_i and at day j. Each day, in search of humans, the zombie population on c_i will try to spread into the surrounding area. That means the possible movements of $Z_j(c_i)$ would be given by Figure 7a.

As mentioned in Sub-section 1.2, every day the zombies try to move to their neighbors according to the geographical elevation of the terrain (given by $\lambda_{0,i}$ factor) and the human population density. In principle, all zombies are forced to move from their node of origin, unless there is no human population around them, which would force them to stay at the node. Then, we can define the contribution of zombies $C_{j+1}(c_0, c_i)$ (Equation 3) from node c_0 to c_i as the number of zombies that move between these cells. This relationship could be posed as a weighted sum with $\lambda_{0,i}$ factor.

$$C_{j+1}(c_0, c_i) = \begin{cases} \left\lfloor \dfrac{\lambda_{0,i} H_j(c_i)}{\sum_{k=1}^{8} \lambda_{0,k} H_j(c_k)} Z_j(c_0) \right\rfloor & \text{if } i \neq 0 \text{ and } \sum \lambda_{0,k} H_j(c_k) > 0 \\ Z_j(c_0) & \text{if } i = 0 \text{ and } \sum \lambda_{0,k} H_j(c_k) = 0 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

We clarify that $\lambda_{0,i}$ is a factor of geographical slope between c_0 and c_i: is zero for a slope higher than 10 degrees, it is one for a slope of zero, and linear between these two values for slopes between 0 and 10 degrees. On the other hand, when handling decimal values it may be the case that decimal contributions are obtained, giving a new problem (it is not possible that 1.5 zombies moves through nodes!). To solve this, we round the contribution result. The remaining number of zombies should keep on the same node (assuming that they did not change nodes). For this, we define the set of remaining zombies $\hat{Z}_{j+1}(c_0)$ in Equation 4.

$$\hat{Z}_{j+1}(c_0) = Z_j(c_0) - \sum_{k=0}^{8} C_{j+1}(c_0, c_k) \tag{4}$$

Ideally, $\hat{Z}_{j+1}(c_0) = 0$ if the entire zombie population spreads to its neighbors as a whole. Now, we define $z_j^l(c_i)$ as the zombies sub-population with age l, gives in days. We know that a zombie can be no more than 15 days old, so $l = \{0, 1, 2, \cdots, 14\}$, and thus $Z_j(c_i) = \sum_{l=0}^{14} z_j^l(c_i)$. This allows, together with $C_{j+1}^l(c_i, c_k)$ as the zombie contribution from nodes c_i to node c_k ($c_k \in \mathcal{N}_i$ as the neighbors of c_i) and age l, to define the propagation dynamics by means of the following algorithm:

Step 0. Updating zombies ages, eliminating those zombies older than 15 days.

$$z_j^l(c_i) = \begin{cases} z_j^{l-1}(c_i) & \text{if } 0 < l \leq 15 \\ 0 & \text{otherwise} \end{cases}, \qquad \text{with } l = \{0, 1, 2, \cdots, 15\}$$

Step 1. Estimate the contribution of zombies $C_{j+1}^l(c_i, c_k)$ in the entire network as well as the remaining subsets $\hat{z}_{j+1}^l(c_i)$. This enables the calculation of the zombie population on c_i.

$$z_{j+1}^l(c_i) = \sum_{c_k \in \{\mathcal{N}_i, c_i\}} C_{j+1}^l(c_k, c_i) + \hat{z}_{j+1}^l(c_i)$$

Step 2. Calculate the number of human deaths: each zombie is capable of killing 10 humans, who will become zombies. The new zombies will clearly have an age of zero.

$$H_{j+1}(c_i) = \begin{cases} H_j(c_i) - 10 Z_{j+1}(c_i) & \text{if } 10 Z_{j+1}(c_i) \leq H_j(c_i) \\ 0 & \text{otherwise} \end{cases}$$

$$z_{j+1}^0(c_i) = H_j(c_i) - H_{j+1}(c_i) = \begin{cases} 10 Z_{j+1}(c_i) & \text{if } 10 Z_{j+1}(c_i) \leq H_j(c_i) \\ H_j(c_i) & \text{otherwise} \end{cases}$$

Step 3. Calculate the amount of human resistance: each surviving human is able to annihilate 10 zombies, which will never revive again. Each zombie has the same probability of dying, regardless of its age.

$$z_{j+1}^l(c_i) = \begin{cases} \left\lfloor z_{j+1}^l(c_i) \left(1 - 10 \dfrac{H_{j+1}(c_i)}{Z_{j+1}(c_i)}\right) \right\rfloor & \text{if } 10 H_{j+1}(c_i) \leq Z_{j+1}(c_i) \text{ and } Z_{j+1}(c_i) \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

Step 4. Updating current day in stocks for future iterations.

$$z_j^l(c_i) = z_{j+1}^l(c_i)$$
$$H_j(c_i) = H_{j+1}(c_i)$$

Note: It is easy to demonstrate in step 3 that $Z_{j+1}(c_i) = Z_{j+1}(c_i) - 10H_{j+1}(c_i)$ if $10H_{j+1}(c_i) \leq Z_{j+1}(c_i)$ else 0, which shows that the zombie population is being reduced in proportion to 10 times the human population.

5.2 Description of actions set

As mentioned in the Sub-section 1.1, two possible actions can be implemented as preventive and control measures of the epidemic. Each one has repercussions on the propagation dynamics, directly affecting the behavior of the equations described in Sub-section 5.1. To determine the changes they produce, let us take $c_i^* \in C_i^*$ as the set of nodes directly affected by the actions.

1. **Reinforcements by military troops:** Two months after the beginning of the epidemic, the EU decides to send military troops to 20 nodes. Each troop is in charge of eliminating the zombie population of that node, so $z^l_{j_m}(c_i^*) = 0 \; \forall l$ and for j_m = October 19th, 2019. In addition, the troops are in charge of making it impossible for zombies to pass through the node. This measure can be interpreted as a change in the elevation factor, given by Equation 5.

$$\lambda^*_{k,i} = \begin{cases} \lambda_{k,i} & \text{if } j < j_m \text{ or } c_i \notin C_i^* \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

   Where $\lambda^*_{k,i}$ is the new λ factor.

2. **Nuclear bombs:** Four months after the start of the epidemics, the EU takes the decision of using nuclear weapons to save the rest of humanity. The development of this action is the same as the reinforcement with military troops, except that on the day they explode (j_b = December 19th, 2019) they also eliminate the human population in the affected nodes, i.e. $H_{j_b}(c_i^*) = 0$.

With the definition of the mathematical scheme, the results after implementing the algorithm will be presented.

5.3 Propagation simulation

The algorithm was implemented to predict the arrival of the zombies in Brest, in order to estimate the time scientists will have to carry out the planning of the execution of nuclear bombs and the deployment of military forces. We found that the zombies arrive in Brest approximately 9 months after the beginning of the spread of the virus. By this date (Figure 8), only 11.94% of the total population is alive and 4.11% is zombie. That is, 83.95% of the total population (2.47 million people) has died from the disease. See all the animation in the spread results without actions link.

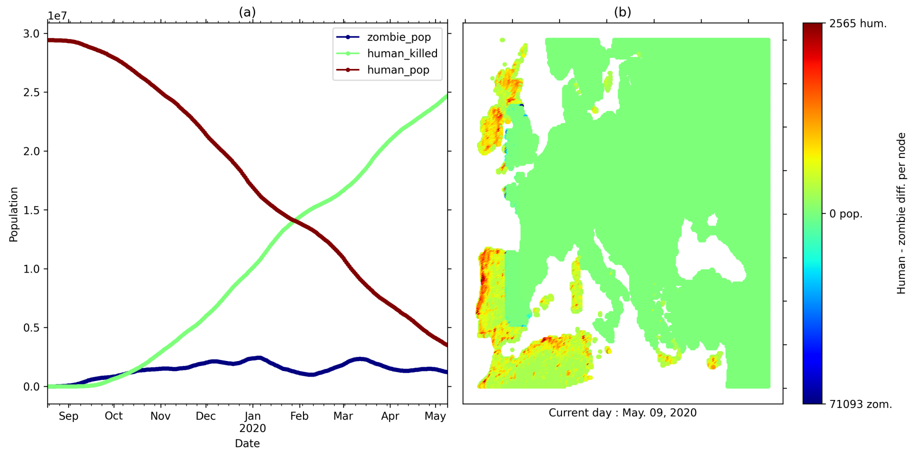

Figure 8: Evolution of the epidemic of (a) total population density of the three groups and (b) difference of populations for each node.

Knowing that the zombies will arrive in Brest on May 9 next year, the military forces will aim to slow the spread of the virus as much as possible by cutting off the routes with the greatest possible flow of connections to the center of Europe.

6 Spreading Blockers Nodes

The structural properties of a dynamic network usually reveal important information about its dynamics and function. This is particularly true if we take into account the relationship between the position occupied by a node in a static graph and the role played by the node for the evolution of a dynamic process. For instance, not all nodes have the same impact on the transmission of a disease or virus over a network: intuitively, the nodes having a higher number of neighbours should contribute much more to the spreading than nodes having few connections. However, we observe that not just the number of edges is important to identify good spreaders, since also the actual organisation of these edges has an impact on the speed of the spreading process. In fact, nodes mediating a large number of shortest paths are indeed those that contribute the most to the transmission of diseases and information over a network. The identification of nodes that play a central role, i.e., nodes having high centrality is a good approach to find the spreading blocker nodes that could help us to stop the virus to arrive to Brest.

6.1 Military deployment

The betweenness centrality between a node within the network is the range of shortest paths between 2 different nodes within the network in which a given node seems. this is often a vital metric within the network as a result of it can be used to determine "spread blocker nodes" within the network. In the context of time-varying network analysis,time-dependent transfer points are identified utilizing the centrality measure between points and time intervals. [5]

A specific node in the network has a higher interrelation score if it is on the shortest paths connecting many other areas of the map, so it will be in a position to propagate a virus faster. This transfer characteristic is very important in dynamic networks. In this context, the importance of a node stop depends not only on its location, but also on the elevation, human population and above all it serves as a transfer point to reach many places in the fastest possible way.

Given two nodes, there may be more than one shortest path between in the network, all with the same length. For example, if nodes O and P are not connected to each other but have two common neighbors neighbors A and S, there are two distinct shortest paths of length two going from A to S. To go from O to P: $O - A - P, O - S - P$. Let δ_{hj} be the total number of shortest paths from h to j and $\delta_{hj}(i)$ be the number of these shortest paths passing through node i. The betweenness of i is defined as:

$$b_i = \sum_{h \neq j \neq i} \frac{\delta_{hj}(i)}{\delta_{hj}} \tag{6}$$

In order to select the cells where we are going to deploy the military forces, a relationship was made between the betweeness of the network and the number of zombies in the network, since the soldiers would eliminate the zombies, so we wanted to eliminate as many zombies as possible, while also choosing critical nodes to slow down the spread of the virus.

For this it was decided to normalize the attributes of betweeness and number of zombies and add them with a 50% ratio to their respective node, this in order to consider both variables when deploying a troop to a node.

The measure that we used to identify the critical nodes for the military forces is D = zombies percentage + betweenness, the nodes selected to deploy the troops were the following:

Table 1: Nodes with military troops.

Node ID	U59569	U59533	U26053	U26035	U32133	U56302	U59533	U26059	U26027	U59554
D	0.2109	0.3536	0.3444	0.5330	0.3051	0.2848	0.4152	0.2812	0.5105	0.2040
Node ID	U59527	U59531	U59532	U26026	U55959	U26030	U47909	U26058	U26057	U26029
D	1.0	0.2043	0.2231	0.2466	0.4868	0.2003	0.2336	0.2148	0.2628	0.2133

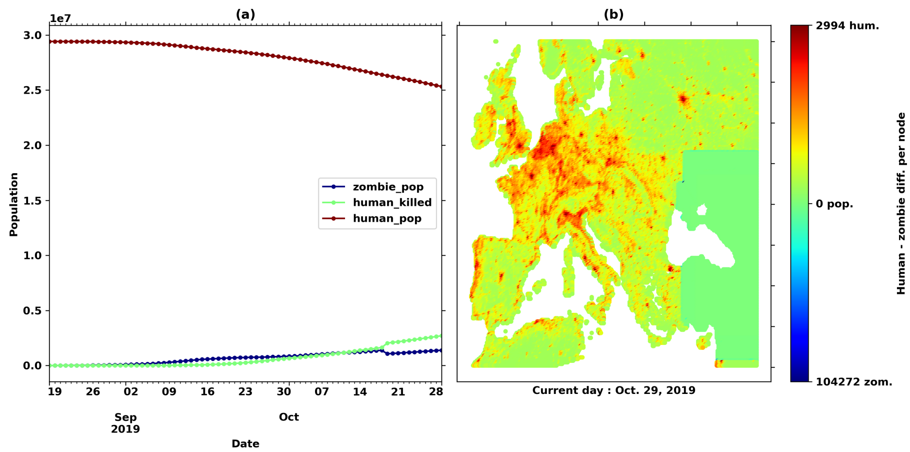

Figure 9: Military cells deployment

In Figure 9 it is observed that by deploying the military troops the zombie population decreased because they were eliminated and the growth of the spread of the virus and the number of zombies increased in a more controlled way, these spread blocker nodes allow to delay the time of spread of the virus until the nuclear bombs can be deployed and decrease the number of human deaths. We show all the simulation in spread results without military action link.

6.2 Cell bombing with nuclear bombs

To select the cells in which the nuclear bombs should be deployed, it was decided to observe the spread of the virus after placing the troops, in the 4th month two different strategies were developed.

1. The cells with the highest number of zombies were killed with a frequency of 15 days
2. The days in which the maximum number of zombies in the graph is greater than the average number of humans alive in an instant of time.

To select the cells to which a nuclear bomb would be sent, it was decided to prioritize the edge of the wave of zombies to eliminate as many zombies as possible and also to immunize the nodes that serve as a bridge from one part of the graph to another in order to delay the speed of propagation, to do this it was decided to select the threshold of zombie propagation, this was done by selecting in a snapshot of time the most critical nodes and sending nuclear bombs in a window of $[1, 15]$ days because we wanted to preserve a relationship between the least amount of bombs sent and the dead humans with respect to the maximum life time of a zombie.

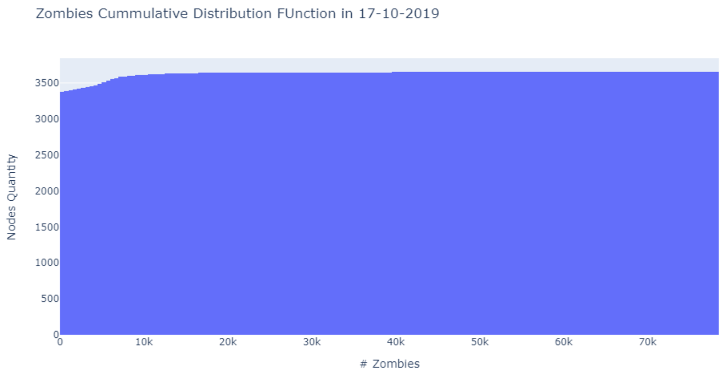

Figure 10: Cumulative Distributive Function of zombies propagation

In Figure 10 we can observe the histogram that calculates the cumulative distribution function on the current nodes that contain zombies,to calculate the number of nodes that we would bombard with a nuclear bomb, from the histogram we define a β factor that is defined by the difference between the number of nodes with zombies that started and ended in a time instant t at the network G.

Table 2: Experiments carried out through the different simulations.

β	Total human population	Total human killed	Bombs number	Bombardment frequency	Date
0	**19180217 (65.18% of all population)**	**10245568 (34.82% of all population)**	3683	15D	**18-10-2019**
0.05	18073721 (61.42% of all population)	11352064 (38.58% of all population)	**504**	15D	16-01-2020
0.1	11331747 (38.51% of all population)	18094038 (61.49% of all population)	1460	15D	30-05-2020
0.3	19121826 (64.9% of all population)	10303959 (35.02% of all population)	3348	1D	21-12-2019
0.4	19095000573 (64.89% of all population)	10330212 (35.11% of all population)	523	1D	03-01-2020
0.6	19165014 (65.13% of all population)	10260771 (34.87% of all population)	3483	1D	20-12-2019
0.8	460437 (1.56% of all population)	28848544 (98.04% of all population)	559	15D	**18-10-2019**

Our initial hypothesis goes back to prioritize the lives of people and save as many people as possible, taking this into account the parameters that adapts more to the solution sought and have a better performance in the simulation is using a $\beta = 0$ as can be seen in the Table 2 it is the simulation that saved more people (19180217, 65. 18% of the entire population), however to obtain this methodology requires the use of 3683 nuclear bombs which means that there will be a considerable amount of areas that cannot be inhabited again for a long time (50 years). It can also be observed that with a $\beta = 0.05$, a very good result is obtained although the number of people alive is lower, however the number of pumps used does vary since many fewer pumps are used (504).

7 Final strategy for saving the wold

Taking into account the information that managed to leak about the zombies, and taking into account that the last living person was recorded on August 18, 2019, it was possible to model the pandemic with graphs.

The propagation model designed allowed us to predict that the zombies would arrive in the city of Brest (where the work team is located) approximately 9 months after the beginning of the pandemic. On the other hand, it allows to observe the way in which the zombies could move around Europe. For example, although the city of Rinze is surrounded by mountains, the zombies manage to move through the whole coast surrounding the mountains. In the case that the persons could be relocated, this information could be useful in alerting the nearby population and could save more lives. additionally, it is observed that some people located on islands could be saved because zombies do not swim, this could be a good location for the most vulnerable population (children, the elderly, pregnant women, etc.).

The objective with the offered troops, which would be ready in October, is to slow the spread and buy time to make calculations. Given that in two months, when the troops will be ready, the zombies are still far away from Brest, that is why the bombs were placed in border areas near the Russian territory. Although a slight decrease in the zombie population is observed, these troops are not able to completely eliminate the zombie population. Therefore, the plan to determine the points where atomic bombs should be placed is being continued.

The Table 2 presents the result of several experiments performed for different parameter settings. Considering an infinite number of bombs and the objective is to save as many people as possible, 3683 bombs are required, with which 65.18% of the population is saved.

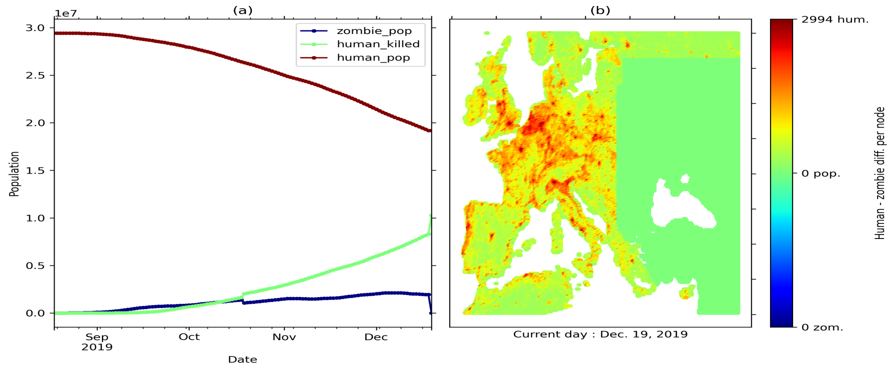

Figure 11: Final view of human and zombie population after bombs

Note: Given the short duration of the simulation in the process of eradicating the zombies using $\beta = 0$, we decided to show the simulation with the least amount of bombs ($\beta = 0.05$). The link to the spread results with nuclear bombs action shows the simulation.

8 Conclusions

In the present paper, a model based on graph theory was developed to describe geospatially the European continent, allowing to load attributes to each node, as well as to describe the elevation relationship of the terrain across the edges. The interactions between the three types of populations (humans, zombies and dead people) were denoted in the form of an algorithm, allowing to predict with its execution key aspects such as the arrival of the virus to the city of Brest, as well as the location of the zombies for the planning of the military deployment and execution of military bombs. Using 20 military troops and 3683 bombs, the pandemic was eradicated on December 19th, 2019.

The team of data scientists, located in the city of Brest, will be safe until 9 months after the start of the pandemic, the zombies would arrive the 9 May of 2020, this estimation was made thanks to the propagation model designed using graph theory.

It was observed that although the military forces eliminated a large number of zombies and slowed down the spread of the virus two months after the start of the virus, as time passed the zombies recovered and advanced rapidly, meaning that only 20 troops using this method did not have a significant impact on the dynamics of the virus.

Thanks to the propagation model, it is possible to estimate the way in which the zombies move across the continent, this information could be useful in a scenario in which it would be possible to relocate people to safer places. On the other hand, we show that people located on some islands could be saved due to the difficulty of the zombies to swim. These could be relocation zones for the most vulnerable population, such as children, elderly people, pregnant women, etc.

The methodology used to save the world and kill all the zombies consists of bombing the nodes at the border where the first line of the spread of the virus is located and where the largest number of zombies are clustered. The results of the different experiments performed showed us that there are several results in which we can reduce the number of bombs, saving money and deployment infrastructure, but a greater number of people would die. That is why we decided to use a great number of bombs in order to prioritize the number of people's life

Finally, we demonstrated that with the use of 3683 bombs it was possible to eradicate the spread of the virus, saving more than 60% of the population compared to the 29 millions of inhabitants at the beginning of the simulation. Unfortunately more than 30% of the humans died in the epidemic, as well as 828675 Km^2 of land were affected, which cannot be inhabited for more than 50 years. However, this solution is considered the most viable in terms of saving as many humans as possible four months after the spread of the disease.

Annexes

All documentation and development code is available in our named repository: zombies-spread-dynamics

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