Master 1 BME | Biomedical Modeling | 09/12/2019

Modeling a zombies' attack outbreak

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Zombie epidemic models provide a useful tool for studying real-life disease outbreaks. The populational dynamics of zombie epidemic resembles the contagious disease outbreaks and enables scientists to study changes in hypothetical scenarios with different parameters and approaches. In this project, we provide various models that simulate different mechanics and scenarios for zombie epidemics exclusively. In models without any intervention operations, we noticed quick decline and eventual elimination of healthy population when following data from famous zombie apocalypse movies that was previously extracted by other researchers. To study different options for fighting back the epidemics, we developed models with different mechanics for cure and military intervention. Therefore, we show the necessity for in-depth analysis and decision-making in deployment of military to the infection site, fast development of cure and its effective spread strategy. Additionally, different models are developed to compare zombie viral infection outbreak and more supernatural scenario of undead resurrection from the dead.

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INTRODUCTION

Mathematical modelling of different disease outbreak scenarios can be a valuable tool when studying dynamics of infectious diseases in population. In the case of epidemic, predictive models provide valuable information for fast decision-making and help in taking preventive measures to halt the progression of disease in its early stages [1]. In given project, a various scenarios of Zombie infection outbreaks are investigated.

The term *zombie* has its roots in Haitian folklore, where it was used to characterize someone brought back from the dead through specific methods, such as rituals or/and black magic, usually with a goal to assign them manual labour [2] (See **Figure 1**, Left). The concept was widely adopted with slight variations by Western culture in the beginning of 1930s through literature (*The Magic Island* [3]) and cinema (*White Zombie* [4]). In modern media, zombies are usually depicted as flesh-consuming aggressive individuals with distinct visual characteristics (See **Figure 1**, Right), whose behaviour is caused by a viral infection [5, 6] or some other variable (divine intervention [7], radiation [8]).

Figure 1 | Difference between Haitian and modern Western depiction of zombies. Left: *Zonbi* by Haitian artist Wilson Bigaud, 1939. **Right**: Scene from *Shaun of the Dead* (2004) [5].

In books and movies, "zombification" (turning into a zombie) takes place through different mechanisms – individuals can become zombies through resurrection from dead, being in contact with other infected individual, bite by a zombie, etc. Those processes can be mapped out in a compartmental models to better visualize population dynamics during zombie outbreak (See **Figures 2** [Left]**, 3, 4** [Right]). In such graphs, boxes depict a state (or a class) of an individual and arrows a process of changing from one state to another. Based on first article studying viral zombie epidemic scenarios, following states/classes of an individual could be established for a basic model of zombie outbreak with latent infection [9] (optimized to follow previous articles on epidemology by [10]):

Susceptible (**S**) individuals represent a part of the healthy human population vurnable to infection/zombifiation (not immune or protected by other variables). Individuals in the *suspectible* state are mainly responsible for eliminating the *zombies*.

Exposed (**E**) are infected individuals in process of turning into a zombie due to a failed encounter with one. This state can be characterized by the incubation period of virus. In most cases, the capabilities of *exposed* individuals are halted, making them less effective (or completely incapable) in fighting back *zombies*.

Zombies (**Z**) are individuals responsible for forcing *suspectible* part of population into states that eventually result in more individuals as *zombies*. Depending on the context and model, successful encounter for a *zombie* could result in victim (*susceptible*) turning into *exposed* part of population (in case viral epidemic).

Removed (**R**) are permanently eliminated individuals, who cannot be resurrected as *zombies*. Usually *zombies* still need brains to function, so in case of serious damage to individuals brain (through crashing the head, burning, etc.) individuals cannot be brought back as *zombies* or *susceptibles* (if a cure has been found).

Depending on scenario, more classes could be used to improve the model based on how we want to segment the population. Originating from real-life epidemographical modelling (with the exception of *zombie* class and different uses of *infected* and *exposed*), previously mentioned states are fundamental to simplified viral zombie epidemics models and have also been adopted researchers invested in modelling zombie outbreaks [9,10,11]. Additionally, processes that govern movement between states were specified in [9] (See **Figure 2**, Left) for a model with latent infection:

Infection is a process in which a *susceptible* individual is encountered by a *zombie*, and becomes *exposed* as a result. In this case *susceptible* loses the encounter.

Outbreak is a process in which a *exposed* individual becomes a *zombie*. For example in scenarios with latent phase, this class is essential to improve models accuracy.

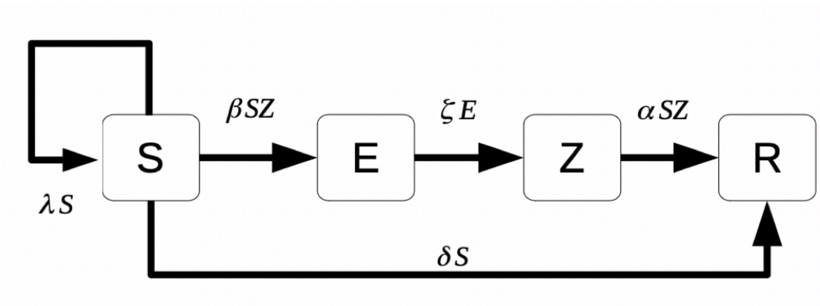
Destruction is a process in which a *susceptible* individual is encountered by a *zombie*, which becomes *removed* as a result. In this case *zombie* loses the encounter.

Birth is a process where a new individual is added to the population. It is dependent on the amount of *susceptibles*.

Death is the process, where *susceptible* individual becomes *removed* through natural causes or suicide.

It is shown that the principle dynamics of viral zombie outbreak resemble epidemic models of disease, and could provide useful information for better understanding real-life scenarios such as spread of Influeza in population [10]. Inspired by the pop-culture, previous studies on zombie epidemics models rely on data from movies such as *Night of the living dead* [12], a famous horror movie from 1968, and *Shaun of the Dead*

[5], a satire comedy parodizing most of present-day Zombie movies. In article by Witkowski and Blais [10], a deterministic models based on ordinary differential equation (**ODE**) systems were constructed to study changes in populations during zombie outbreak following extracted data from previously mentioned movies. In this project, same extracted information is used to test models with different classes and complexity.



$$
\begin{aligned}
S' &= -\beta SZ \\
E' &= +\beta SZ - \zeta E \\
Z' &= +\zeta E - \alpha SZ \\
R' &= +\alpha SZ
\end{aligned}
$$

Figure 2 | Compartmental model of viral zombie epidemic with latent infection (SEZR+bd model) and its corresponding system of differential equations [13]. Left: (**S**) Susceptible (healthy), (**E**) Exposed infected, (**Z**) Zombie and (**R**) Removed individuals. Arrows depicted as (**λS**) birth, (**βSZ**) infection, (**ζE**) outbreak, (**δS**) natural death or suicide, and (**αSZ**) destruction. **Right:** System of differential equations for **SEZR+bd** model. Greek letters symbolize the relative speed of processes. Multiplication is used to model participation of individuals from different classes in certain processes.

ODEs are used to mathematically describe the changes in the system on each time step and allow the dynamic modelling of epidemic scenarios. Therefore, for every model a corresponding mathematical representation as system of ODEs will be implemented (See **Figure 2**, Right).

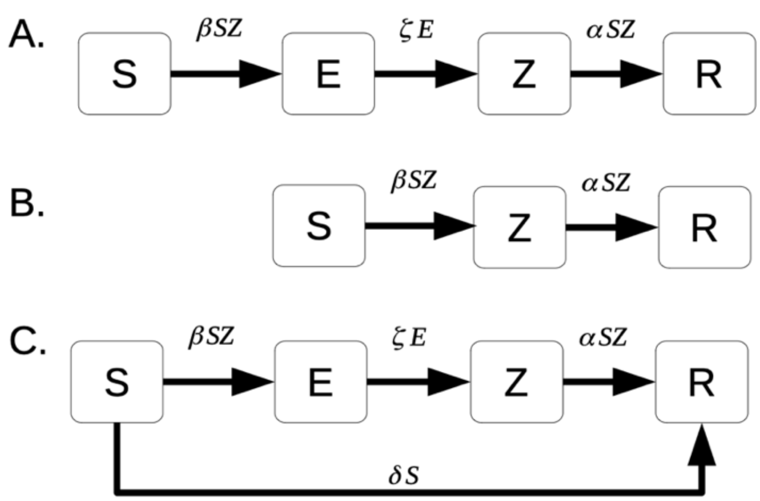


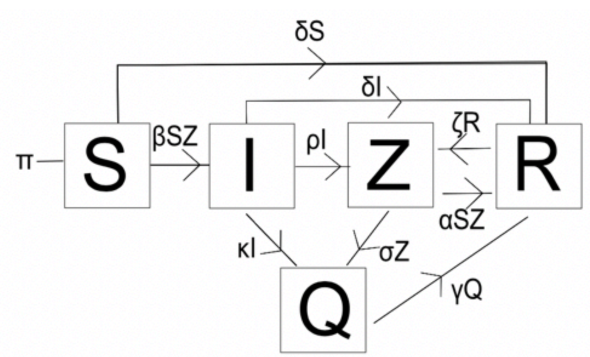
Figure 3 | Simplified models for viral zombie epidemic. (**A**) Simplified SEZR model without deaths and births (**B**) Simplified model without latent incubation phase/state (**C**) Simplified SEZR model without births and natural deaths taken into account due to short time scale (suicides remain). See Figure 2 for more details on symbols depicted.

Depending on the level of abstraction, simpler models can be adapted to study populational changes during zombie epidemic. In some conditinons simpler model could result in same performance as a complex one. First, the influence of births and deaths on the model is investigated by removing only births (See **Figure 3**, C) and then both of the processes (See **Figure 3**, A). Those scenarios are more realistic when zombie epidemic takes place in short time scale (in this case the amount of new individuals born into the population is too small to be taken into account). Second, by leaving out the latent phase (*exposed* state of individual), it we can study how a failed encounter converts a *susceptible* individual directly to *zombie* (See **Figure 3**, B).

Models with additional states and processes were suggested by Munz et al. In [9], scenarios with *quarantined* (**Q**) individuals (See **Figure 4**, A, Right) and cure (See **Figure 4**, B, Right) were further investigated, resulting in more complex systems of differential equations (See **Figure 4**, A and B, Left). It is important to notice that in those models resurrection of zombies has been allowed from *removed* class (although we previously categorized individuals in state **R** permanently removed). This categorization is dependent on model and can vary between different publications. The could be solved by introducing additional class (*Dead*) to the model in scenarios, where resurrection is allowed and differentation between removed and dead individuals could become useful. *Dead* (**D**) is a state to classify killed individuals with a potential to be resurrected as zombies (*removed* individuals follow initially stated description).

A

$$\begin{aligned} S' &= \Pi - \beta SZ - \delta S + cZ \\ I' &= \beta SZ - \rho I - \delta I \\ Z' &= \rho I + \zeta R - \alpha SZ - cZ \\ R' &= \delta S + \delta I + \alpha SZ - \zeta R. \end{aligned}$$



B

$$\begin{aligned} S' &= \Pi - \beta SZ - \delta S + cZ \\ I' &= \beta SZ - \rho I - \delta I \\ Z' &= \rho I + \zeta R - \alpha SZ - cZ \\ R' &= \delta S + \delta I + \alpha SZ - \zeta R. \end{aligned}$$

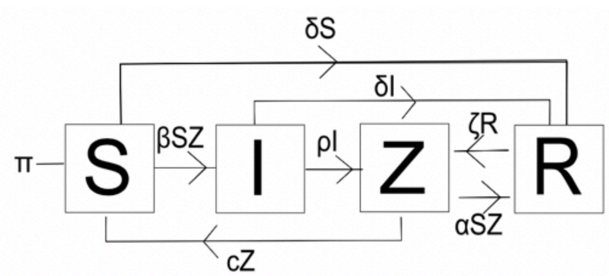


Figure 4 | Advanced models for zombie epidemic [9]. ODEs depicted on the **left** side with corresponding graphical models on the **right**. In article by Munz et al., *infected* state (**I**) is equivalent to *exposed* in other publications. (**A**) Improved SIZR (also known as SEZR) model with *Quarantined* (**Q**) state and **ressurection** process. (**B**) Improved SIZR (also known as SEZR) model with **cure** process. **States:** (**S**,**Z**,**R**) See **Figure 2**. **Processes:** (**π**) Constant birth of new individuals, (**δS**, **βSZ**, **αSZ**) See **Figure 2**, (**cZ**) Curing a *zombie* back to *susceptible*, (**δS**) Suicide or natural death of an *infected/exposed* individual, (**ρI**) disease outbreak, (**ζR**) Resurrection as a *zombie,* (**γQ**) Death of quarantined *infected* or *zombie.* (**κI**, **σZ**) moving an *infected* or a *zombie* to a quarantined state, respectively.

For clarity, we have decided to categorize models with resurrection more supernatural and treat it differently than viral zombie infection. In this project resurrection models do not include *exposed* (also known as *infected* [9]) state leading to outbreak, but instead all the *zombies* are **resurrecting** from the *dead* class. Removed class includes individuals with destroyed brains through suicide and destruction (when *susceptible* destroys a *zombie*). Although, when comparing models for ressurection and viral infection, it is clear that they don't differ from eachother drastically (See **Figure 5**). This is also claimed in [10]. Only aspect that should be taken under consideration is amount of *dead* individuals in the beginning of simulation.

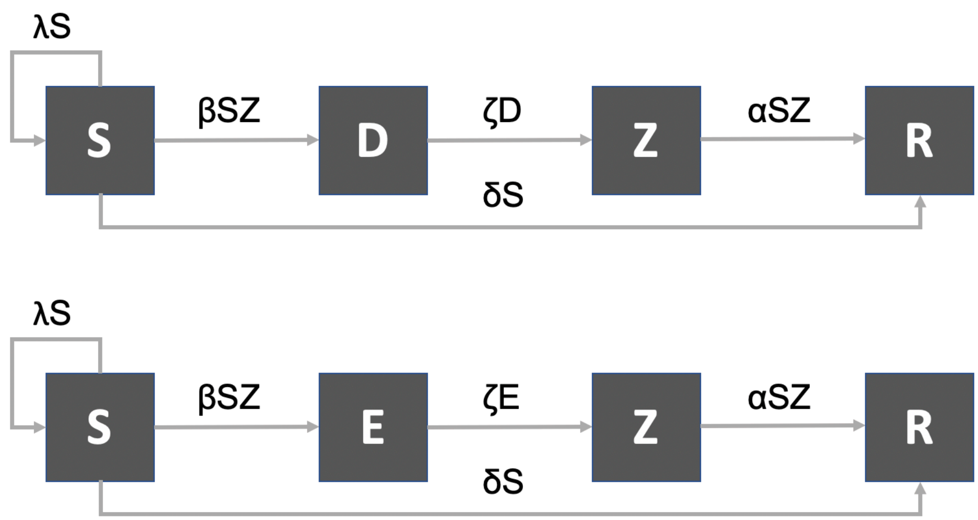


Figure 5 | Comparison of viral infection and supernatural ressurection scenario models for zombie outbreak. Above: Zombie outbreak with ressurection mechanism. (**D**) *Dead* individuals, (**ζD**) Resurrection as a *zombie.* **Below:** Viral infection zombie epidemic model (**SEZR+bd**). See **Figure 2** for additional information on used symbols.

All previously mentioned models are based on mass action dynamics and assume that individuals have equal probabilities for meeting eachother. Geographical data has been utilized in modelling real-life epidemics [14] and could become useful in further development of zombie outbreak models, but for simplification purposes, it has been left aside in this project.

The goal of this project is to simulate models presented here in introduction with main parameters provided by Witkowski and Blais [10] and test modified versions of models provided by Munz et al. [9]. We try to find an optimal level of abstraction for zombie viral infection model. Additionally, a model, where military is distinguished from citizens (*susceptible* class is divided into two) is suggested by author.

METHODS AND MATERIALS

Models for different scenarios were developed to study population dynamics in zombie epidemic. Parameters for infection, outbreak and destruction were obtained from [10] with starting population. For more complex models parameters were applied through trial and error to test different possible scenarios.

(See **Table 1** for parameters tested with every model)

SIMULATION ENVIRONMENT

First, a simulation environment (See **Supplementary Data 1**) was developed to better manage development and testing of models for different outbreak scenarios.

MODELS

Viral zombie epidemic of latent infection with birth and death (**SEZR+bd** model [SEZR+(birth)(death)]; See **Figure 6,** A) was implemented in GNU Octave (See **Supplementary Data 2**) following ODE system and graphical figure suggested in [13].

Next, the changes in population were investigated through removal of birth and death from **SEZR+bd** model resulting in **Simplified SEZR model without births and natural deaths** (**SEZR+d**; See **Figure 6**, B; See **Supplementary Data 3**). It is important to notice that in this case suicide still remained, but the parameter **δ** for deaths was modified. Second, suicide was removed from the ODEs and graphs to establish a model of **viral zombie epidemic with latent infection** (**SEZR** model; See **Figure 6**, C; See **Supplementary Data 4**). Third, a simple model of **SZR without latent phase** (**SZR** model; See **Figure 6**, D; See **Supplementary Data 5**) was constructed and compared to other models with more complexity.

Previously developed models were suggested by [13] and implemented with data from *Shaun of the Dead*, since those models are more useful when studying viral mechanics of zombie outbreak. Parameters for birth and natural death/suicide were choosen relatively small compared to other processes.

Following models investigate further developments of ideas from [9] and [10]. Additionally, we have constructed a model for improved simulation of more supernatural zombie resurrection scenario that fits with *Night of the Living Dead* [12] data from [10].

Viral zombie epidemic with latent infection and cure (**SEZR+bdc** model, [SEZR+(birth)(death)(cure)]; See **Figure 7**, B & C; See **Supplementary Data 6, 7**) was developed with inspired by an approach demonstrated in [9]. Model was modified to ignore resurrection of zombies and mechanism for cure was added through a time-dependent function (See **Supplementary Data 8**). This allows to introduce the cure at certain time point to the population to study how dynamics will change with new parameter being introduced. In this apporach, we implement two different models. In **SEZR+bdc1** we constructed a model that requires *susceptible* contact to administer a drug to *zombie* or *exposed*. For **SEZR+bdc2**, we removed the requirement for direct administration (thus no need for alive *susceptibles* to be present in population). This could be a compatible model when cure is released into the air and no contact of individuals is needed for disease treatment.

As a next step, we developed a **SZR+bd** model (See **Figure 7**, A; See **Supplementary Data 9**), which is more suitable for supernatural scenarios like depicted in *Night of the Living Dead*. We added a *Dead* (**D**) state to distinguish individuals who are permanently *removed* and temporarly *dead*.

Last, we would like to propose a model to study military allocation during zombie epidemic (**SEZR+mc**, SEZR+(military)(cure); See **Figure 8**; **See Supplementary Data 10**). In this case cure is available after time t_s (like in previous models with cure) and can only be administred to *zombies* and *exposed* individuals through direct contact by *military* personel. *Military* is more effective when eliminating *zombies*, but needs to later find balance between administrating cure and destroying *zombies*. Additionally, *military* is deployed to the site of outbreak with constant rate ψ. Furthermore, suicide/natural death was made possible for *exposed* individuals. Since in most cases individuals would have psychologically more reason to consider suicide when they are already *exposed* to the disease. Given model is further development of latent infection model with cure. Parameters were obtained through trial and error.

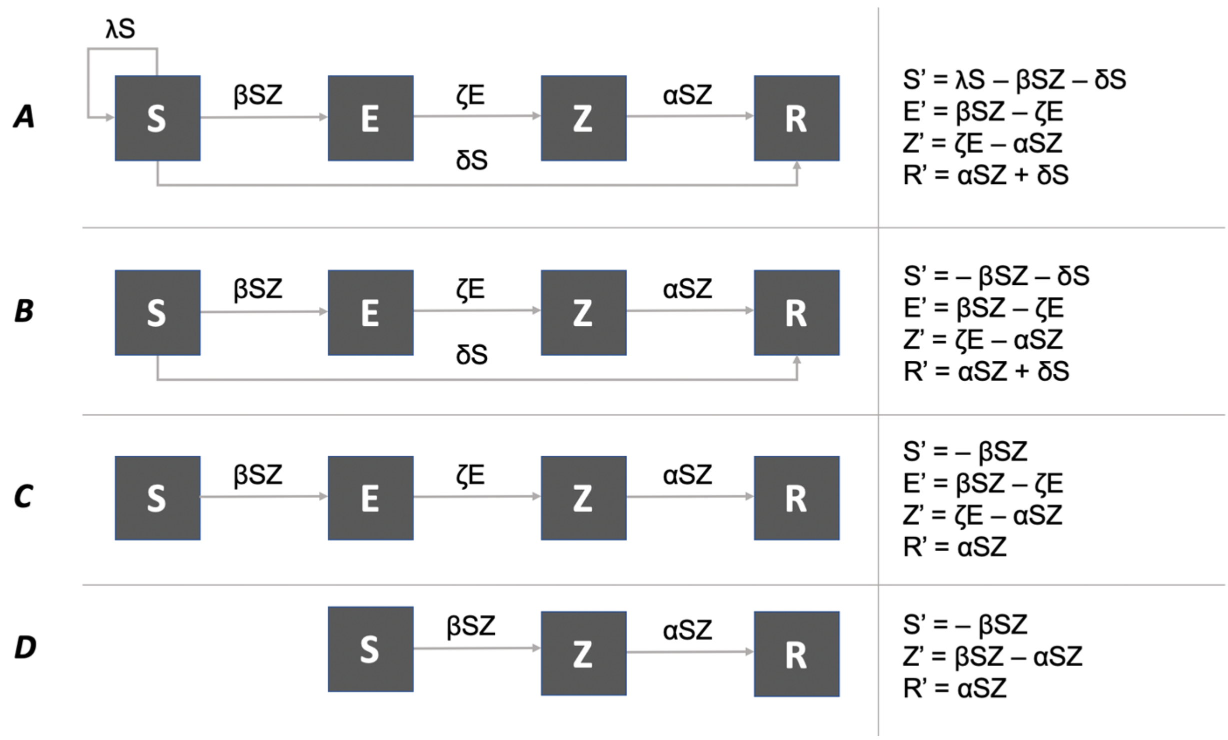


Figure 6 | Applied models for viral zombie epidemic. Left: Graphical representation of models. **Right:** Corresponding systems of ODE. (**A**) model with latent infection with birth and death (**SEZR+bd)** (**B**) Simplified model without births and natural deaths, but with suicides (**SEZR+d**), (**C**) simplified model with latent infection (**SEZR**), (**D**) simplified model without latent phase (**SZR**).

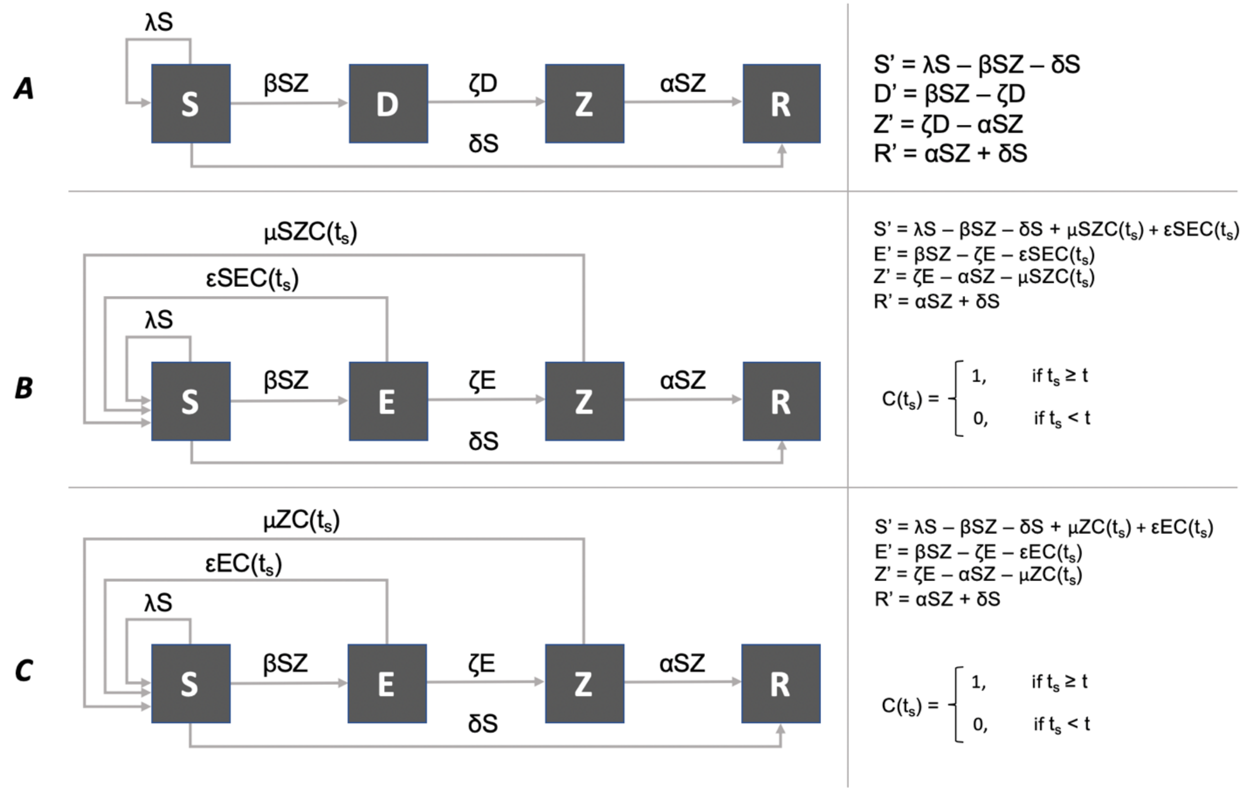


Figure 7 | Modified Zombie outbreak models adapted from Munz et al. [9]. Left: Graphical representation of models. **Right:** Corresponding systems of ODE. (**A**) model adapted for resurrection of zombies (**SDZR**). State **D**: Individuals in *dead* state, (**B**) model with latent infection and manually administred cure (**SEZR+bdc1,** SEZR+(birth)(death)(cure v1)), (**C**) model with latent infection and cure spreaded through air (**SEZR+bdc2,** SEZR+(birth)(death)(cure v2)). Processes: (**ζD**) Resurrection as a *zombie.* (**$\varepsilon SEC(t_s)$**) A susceptible individual curing *exposed* individual if the cure is present, (**$\mu SZC(t_s)$**) A susceptible individual curing a zombie if the cure is present, (**$\varepsilon EC(t_s)$**) An exposed individual cured with a drug spread into the air, (**$\mu ZC(t_s)$**) A zombie cured with a drug spread into the air. **$C(t_s)$** is a function that is started on time t_s and represents a cure made available to population. See **Figure 2** for other not mentioned.

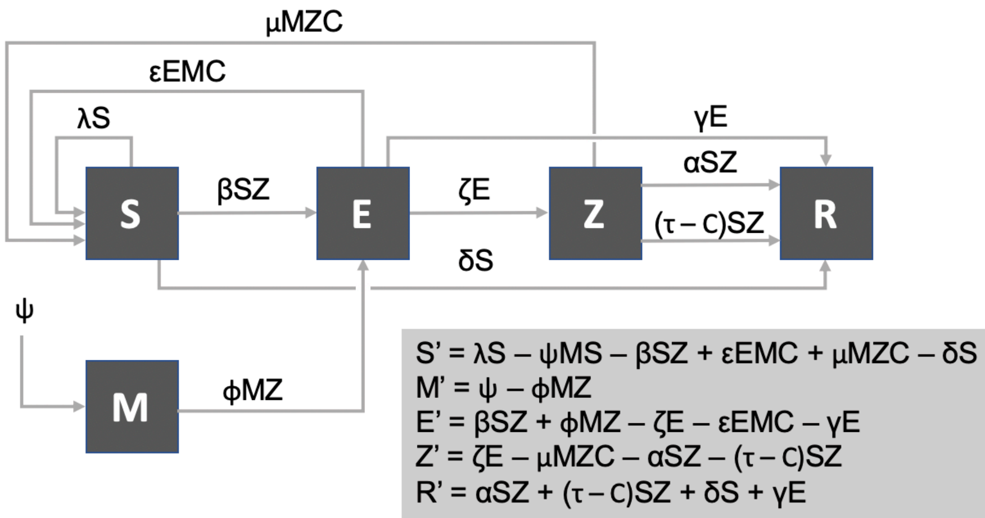


Figure 8 | Adaptive viral zombie outbreak model with military and cure. ODEs brought out in a gray box. Processes and states not mentioned are specified under **Figure 2** and **Figure 6**. **States:** (**M**) Military personel. **Processes:** (**εEMC(t_s)**) A military unit curing an *exposed* individual if a cure is present, (**μSZC(t_s)**) A military unit curing a zombie if a cure is present, (**ψ**) Military personel being deployed to the site of outbreak, (**ϕMZ**) Military unit being infected by a zombie, (**γE**) Exposed individual commiting a suicide or dying natural death, (**(τ – C)SZ**) Targeted attack against zombie by military unit (when the cure is released, military units take some of their resources to curing zombies instead of destroying them).

Table 1 | Parameters used in model testing.

	Base parameters based on *Shaun of the Dead* [10,12]						*	
Models → Parameters ↓	SEZR+bd	SEZR+d	SEZR	SZR	SEZR+bdc1	SEZR+bdc2	SDZR	SDZR+mc
S_o	508.29	508.29	508.29	508.29	508.29	508.29	178.66	508.29
D_o	N/A	N/A	N/A	N/A	N/A	N/A	0	N/A
E_o	1	1	1	N/A	1	1	N/A	1
Z_o	0	0	0	1	0	0	1	0
R_o	0	0	0	0	0	0	0	0
M_o	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100 70/100
α	0.49	0.49	0.49	0.49	0.49	0.49	0.9	0.1
β	0.59	0.59	0.59	0.59	0.59	0.59	1.1	0.8
ζ	2	2	2	N/A	2	2	3.6	0.9
δ	0.05	0.03	N/A	N/A	0.005	0.005	0.1	0.02
λ	0.005	N/A	N/A	N/A	0.005	0.005	0.005	0.05
ε	N/A	N/A	N/A	N/A	0.1	30	N/A	3
μ	N/A	N/A	N/A	N/A	0.005	30	N/A	0.2
t_s	N/A	N/A	N/A	N/A	11/11.1	11/11.1	N/A	5/6 10
ψ	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5
ϕ	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.2
τ	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.7
γ	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.5

(*****) Parameters based on Night of the Living Dead [10, 12]

SOFTWARE AND HARDWARE

Models in this project were implemented in GNU Octave v5.1. GitHub Atom v1.41 text editor and iTerm2 (Build 3.3.6) were used in code development and testing on MacBook Pro 2016 (2 GHz Dual-Core Intel Core i5, 8 GB 1867 MHz LPDDR3, MacOS v10.15). Differential equations were solved using *ode45* methods.

RESULTS

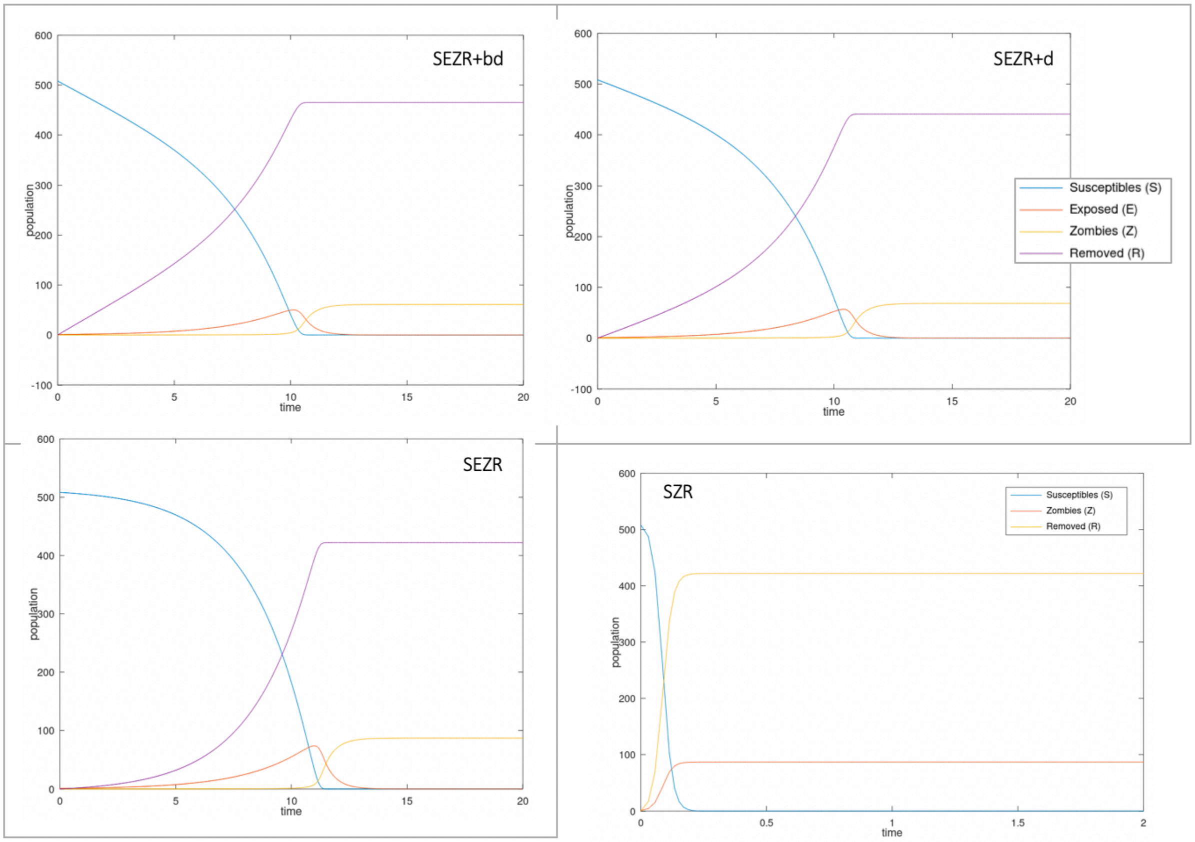


Figure 9 | Results of viral zombie outbreak modelling with data [10] extracted from *Shaun of the Dead.* Parameters stated in **Table 1**.

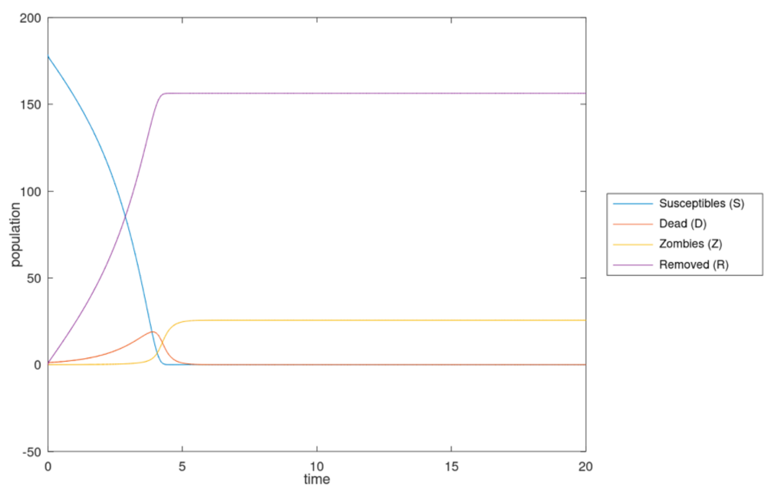
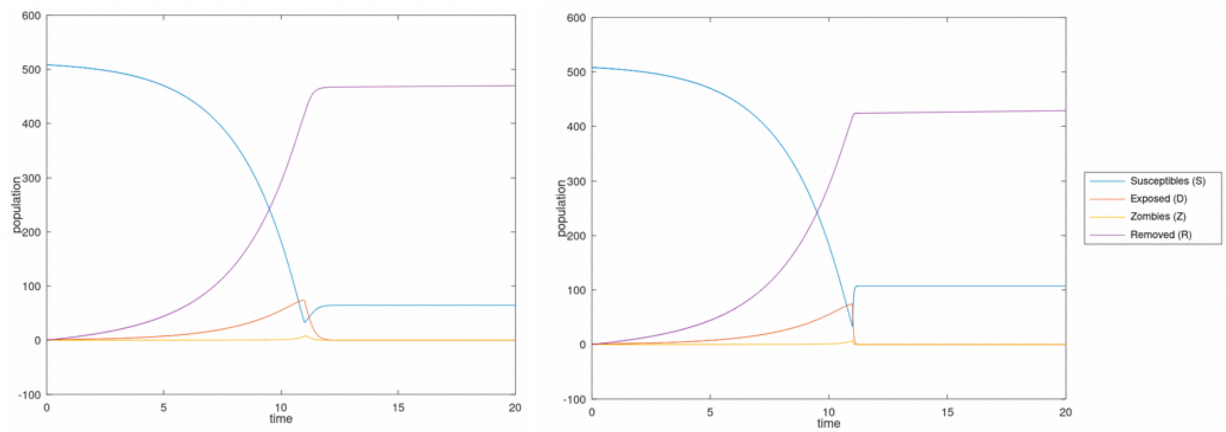


Figure 10 | Results of resurrection model with data [10] extracted from *Night of the living Dead.* Parameters stated in **Table 1** (**SDZR**, adopted from [10] following *Night of the living Dead* (S_o = 178.66)).

Cure released at t_s = 11



Cure released at t_s = 11.1

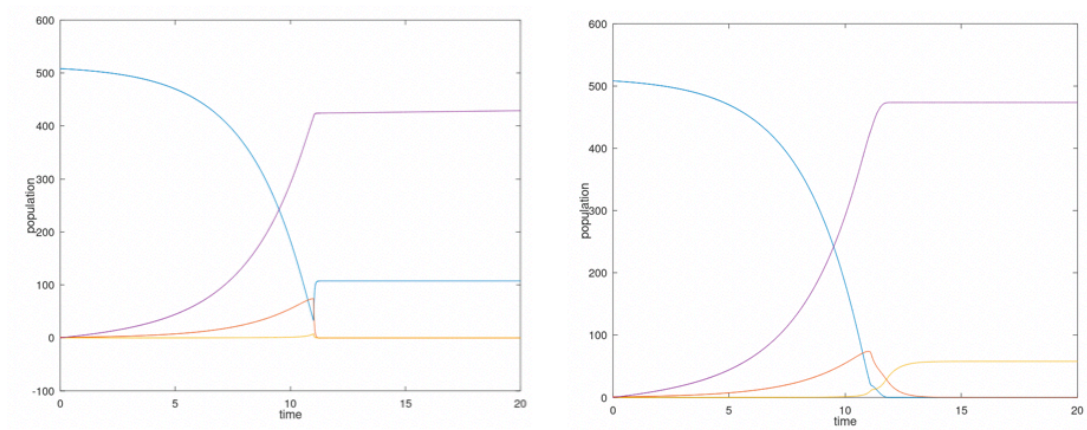


Figure 11 | Comparison of different models for cure mechanics and release timing. Left: Models with manual administration of cure. **Right:** Models with air-spread cure. Parameters stated in **Table 1** (manual administration: **SEZR+bdc1** and **SEZR+bdc2:** air-spread cure).

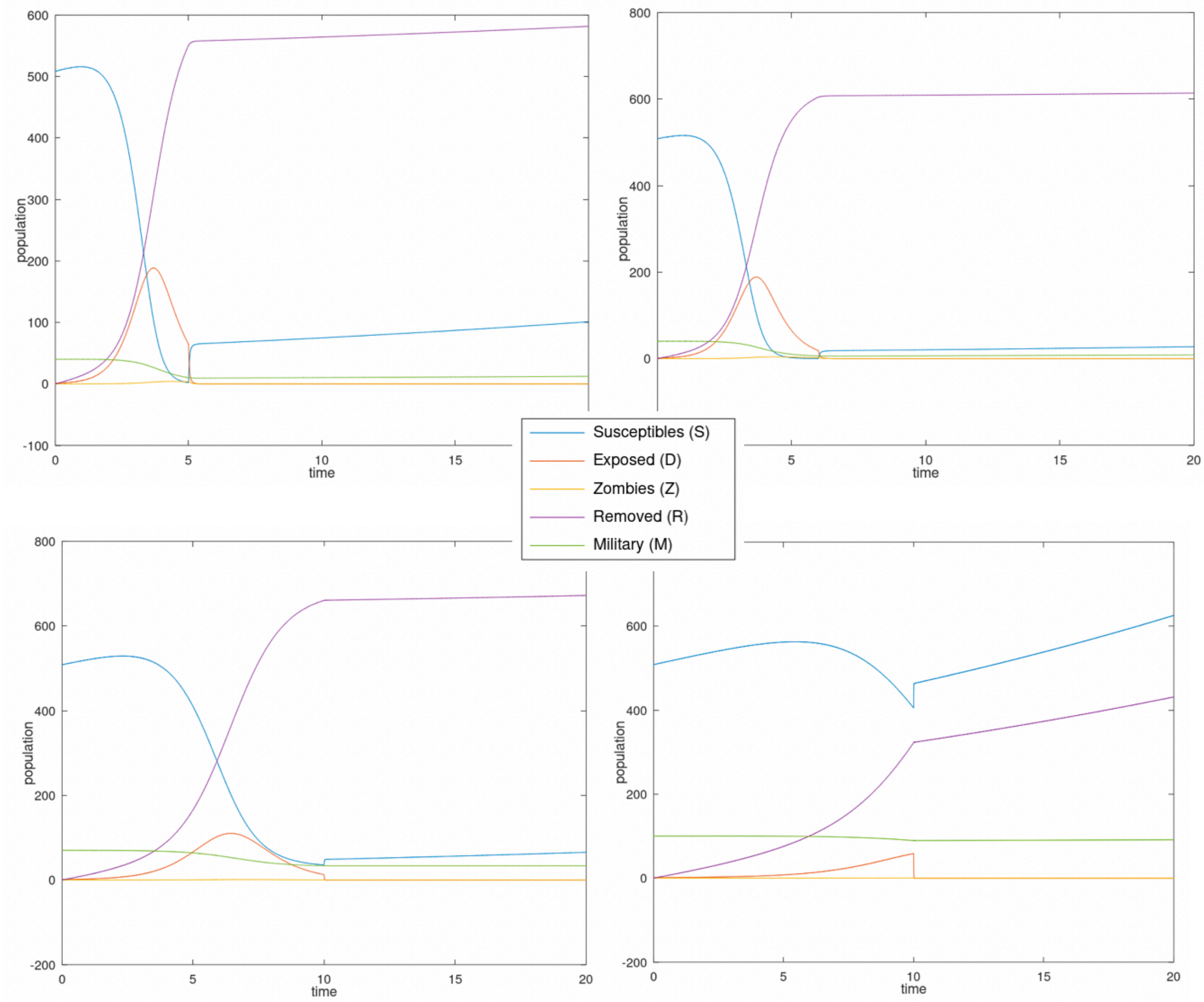


Figure 12 | Results of adaptive model with military and cure. (**Top Row**) Testing model with different cure release timings. **Left:** cure released at $t_s = 5$. **Right:** cure released at $t_s = 6$. (**Bottom Row**) Testing model with different initial sizes of military. **Left:** 70, **Right:** 100. Initial size of population adopted from [10] following *Shaun of the Dead* (S_o = 508.29). Other parameters available in **Table 1** (**SEZR+mc**).

DISCUSSION

First, by observing model behaviour in **Figure 9** (A, B & C), we can deduce that suicides, natural deaths and births contribute little to the outcome of zombie viral outbreak. Although, the importance of latent phase should be emphasized when comparing the results of SZR model (See **Figure 9,** D) with first three including *exposed* state (See **Figure 9**). When observing SZR model, *susceptible* population was eliminated between time 0 and 0.5, while models with latent phase resulted in complete elimination of *susceptible* individuals in a time between 10 and 12. SZR can be a simplified model for scenario, where the infection evolves radically fast and zombification takes place in seconds. Additionally, results of simulation show similarities with outcomes presented in [10].

By studying models on **Figure 9** and **Figure 10**, we can claim that data from both films should result in a complete elimination of *susceptible* population, since in our models no military was implemented in those cases. In addition, models of resurrection and viral infection show similarities in graphical representation. This aspect can be observed from the model scenarios, where curves of population show alike behaviour. In **Figure 10**, curves are compressed more towards starting time due to different input parameters.

Next, we can observe how the release time of a cure can drastically affect the outcome of a model even when changing it by 0.1 (0.9%). We also proved that air-spread cure could be much more effective solution when there is little *susceptible* population left. Smaller difference was present between methods of cure administration when *susceptible* population was greater (See **Figure 11**). Cure was previously applied in the paper by Munz et al., but in this case it did not allow the scenarios, where cure was introduced to the population in the middle of the simulation.

Last, military allocation in zombie epidemic was modelled in **Figure 12**. From the results of experiments, we can deduce that military is also effective in small numbers when cure is being developed and available as soon as possible. Results also show that small size difference in military (70 vs 100) can greatly affect the survival of *susceptible* individuals. Although it is important to mention that given model is not geographically correctly built. Military units usually work together as groups and for that reason given setup does not satisfy the requirement set for our model (See mass action dynamics in the end of introduction).

Conclusion

In this project, dynamic approach was applied with systems of ODE to model populational changes during zombie outbreak. We relied on articles [9], [10], [11] to test previously suggested models and to develop new models for different zombie epidemic scenarios. It was confirmed that different mechanisms for zombification work in similar ways as stated in [9] when comparing scenarios with resurrection and viral infection with latent phase. Additionally, a new approach for modelling cure and military allocation was suggested and tested. Final state for most of the tested models end with the elimination of susceptible population if no cure or military is integrated into the studied scenario.

Attempts of intervention for humanity such as introduction of a cure or a military deployment showed to be effective if applied in the right time and way. This confirms the hypothesis from [10] where it was stated that the major factors that contribute to the positive outcome for susceptibles is the strength and time of intervention. Further developments in the field could include geographical implementation of outbreak models to allow better simulation of group behaviour and military allocation.

References

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SUPPLEMENTARY INFORMATION

Supplementary Data 1 | simulation.m

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% File for plotting graphs

clear all ; close all ; clc


% Set initial parameters according to model.

[t,x] = ode45(@SEZR_mc, [0,20], [508.29,1,0,0,30])

% [t,x] = ode45(@SEZR, [0,20], [508.29,1,0,0])


plot(t,x)

xlabel("time")

ylabel("population")


% Choose one depending on the amount of parameters and model used.

legend({"Susceptibles (S)", "Exposed (D)","Zombies (Z)", "Removed (R)", "Military (M)"}, "location", "eastoutside")

%legend({"Susceptibles (S)", "Exposed (D)","Zombies (Z)", "Removed (R)"}, "location", "eastoutside")
```

Supplementary Data 2 | SEZR_bd.m

```
% Viral zombie epidemic of latent infection with birth and death (SEZR+bd)

function dx=SEZR_bd(t,x)

% ---- States/classes ----

% dx(1) - Susceptiple population

% dx(2) - Exposed population

% dx(3) - Zombie population

% dx(4) - Removed population

%

% ---- Process parameters ----

% alpha – destruction of zombies by susceptible(s) (failed encounter for a zombie)

% beta – infection of susceptible by a zombie (failed encounter for a susceptible)

% zeta – disease outbreak (exposed individual turns into a zombie)

% delta – natural death or suicide of susceptible

% lambda – birth of the new individual

%

% Parameters for alpha, beta, zeta adopted from Table 1 of [13].

alpha = 0.49;

beta = 0.59;

zeta = 2;

delta = 0.05;

lambda = 0.005;


% Initiate a vector of zeros to update state values.

dx = zeros (4, 1);


dx(1) = x(1)*lambda - beta*x(1)*x(3) - delta*x(1);

dx(2) = beta*x(1)*x(3) - zeta*x(2);

dx(3) = zeta*x(2) - alpha*x(1)*x(3);

dx(4) = alpha*x(1)*x(3) + x(1)*delta;

endfunction
```

Supplementary Data 3 | SEZR_d.m

```
% Simplified SEZR model without births and natural deaths (SEZR+d)

function dx=SEZR_d(t,x)

% ---- States/classes ----

% dx(1) - Susceptiple population

% dx(2) - Exposed population

% dx(3) - Zombie population

% dx(4) - Removed population

%

% ---- Process parameters ----

% alpha – destruction of zombies by susceptible(s) (failed encounter for a zombie)

% beta – infection of susceptible by a zombie (failed encounter for a susceptible)

% zeta – disease outbreak (exposed individual turns into a zombie)

% delta – natural death or suicide of susceptible

%

% Parameters for alpha, beta, zeta adopted from Table 1 of [13].

alpha = 0.49;

beta = 0.59;

zeta = 2;

delta = 0.03;


% Initiate a vector of zeros to update state values.

dx = zeros (4, 1);


dx(1) = - beta*x(1)*x(3) - delta*x(1);

dx(2) = beta*x(1)*x(3) - zeta*x(2);

dx(3) = zeta*x(2) - alpha*x(1)*x(3);

dx(4) = alpha*x(1)*x(3) + x(1)*delta;

endfunction
```

Supplementary Data 4 | SEZR.m

```
% Simplified latent infection model (SEZR)

function dx=SEZR(t,x)

% ---- States/classes ----

% dx(1) - Susceptiple population

% dx(2) - Exposed population

% dx(3) - Zombie population

% dx(4) - Removed population

%

% ---- Process parameters ----

% alpha – destruction of zombies by susceptible(s) (failed encounter for a zombie)

% beta – infection of susceptible by a zombie (failed encounter for a susceptible)

% zeta – disease outbreak (exposed individual turns into a zombie)

%

% Parameters for alpha, beta, zeta adopted from Table 1 of [13].

alpha = 0.49;

beta = 0.59;

zeta = 2;


% Initiate a vector of zeros to update state values.

dx = zeros (4, 1);


dx(1) = - beta*x(1)*x(3);

dx(2) = beta*x(1)*x(3) - zeta*x(2);

dx(3) = zeta*x(2) - alpha*x(1)*x(3);

dx(4) = alpha*x(1)*x(3);

endfunction
```

Supplementary Data 5 | SZR.m

```
% Simplified model without latent infection (SZR)

function dx=SZR(t,x)

% ---- States/classes ----

% dx(1) - Susceptiple population

% dx(2) - Zombie population

% dx(3) - Removed population

%

% ---- Process parameters ----

% alpha – destruction of zombies by susceptible(s) (failed encounter for a zombie)

% beta – infection of susceptible by a zombie (failed encounter for a susceptible)

%

% Parameters for alpha and beta adopted from Table 1 of [13].

alpha = 0.49;

beta = 0.59;



% Initiate a vector of zeros to update state values.

dx = zeros (3, 1);


dx(1) = - beta*x(1)*x(2);

dx(2) = beta*x(1)*x(2) - alpha*x(1)*x(2);

dx(3) = alpha*x(1)*x(2);

endfunction
```

Supplementary Data 6 | SEZR_bdc1.m

```
% Viral zombie epidemic model of latent infection and manually administred cure (SEZR+bdc1)

function dx=SEZR_bdc1(t,x)

% ---- States/classes ----

% dx(1) - Susceptiple population

% dx(2) - Exposed population

% dx(3) - Zombie population

% dx(4) - Removed population

% dx(5) – Military personel

%

% ---- Process parameters ----

alpha = 0.49;

beta = 0.59;

zeta = 2;

delta = 0.005;

lambda = 0.005;

epsilon = 0.1;

mu = 0.005;

time_for_cure = 11.1;


% ---- Process parameters ----

% alpha – destruction of zombies by susceptible(s) (failed encounter for a zombie)

% beta – infection of susceptible by a zombie (failed encounter for a susceptible)

% zeta – disease outbreak (exposed individual turns into a zombie)

% delta – natural death or suicide of susceptible

% lambda – birth of the new individual

% epsilon – cure administration to exposed individual by susceptible

% mu – successful cure administration to a zombie by susceptible

% time_for_cure - time when the cure is invented and made available


% Initiate a vector of zeros to update state values.

dx = zeros (4, 1);
```

```
dx(1) = x(1)*lambda - beta*x(1)*x(3) - delta*x(1) + cure(t,time_for_cure)*x(2)*x(1)*epsilon + cure(t,time_for_cure)*x(3)*x(1)*mu;

dx(2) = beta*x(1)*x(3) - zeta*x(2) - cure(t,time_for_cure)*x(2)*x(1)*epsilon;

dx(3) = zeta*x(2) - alpha*x(1)*x(3) - cure(t,time_for_cure)*x(3)*x(1)*mu;

dx(4) = alpha*x(1)*x(3) + x(1)*delta;

endfunction
```

Supplementary Data 7 | SEZR_bdc2.m

```
% Viral zombie epidemic with latent infection and air-spreaded cure (SEZR+bdc2)

function dx=SEZR_bdc2(t,x)

% ---- States/classes ----

% dx(1) - Susceptiple population

% dx(2) - Exposed population

% dx(3) - Zombie population

% dx(4) - Removed population

% dx(5) – Military personel

%

% ---- Process parameters ----

alpha = 0.49;

beta = 0.59;

zeta = 2;

delta = 0.005;

lambda = 0.005;

epsilon = 30;

mu = 30;

time_for_cure = 11.1;


% ---- Process parameters ----

% alpha – destruction of zombies by susceptible(s) (failed encounter for a zombie)

% beta – infection of susceptible by a zombie (failed encounter for a susceptible)

% zeta – disease outbreak (exposed individual turns into a zombie)

% delta – natural death or suicide of susceptible

% lambda – birth of the new individual

% epsilon – successful treatment of exposed individual

% mu – succesful treatment of zombie

% time_for_cure - time when the cure is invented and made available


% Initiate a vector of zeros to update state values.

dx = zeros (4, 1);
```

```
dx(1) = x(1)*lambda - beta*x(1)*x(3) - delta*x(1) + cure(t,time_for_cure)*x(2)*epsilon + cure(t,time_for_cure)*x(3)*mu;

dx(2) = beta*x(1)*x(3) - zeta*x(2) - cure(t,time_for_cure)*x(2)*epsilon;

dx(3) = zeta*x(2) - alpha*x(1)*x(3) - cure(t,time_for_cure)*x(3)*mu;

dx(4) = alpha*x(1)*x(3) + x(1)*delta;

endfunction
```

Supplementary Data 8 | cure.m

```
% Function that controls the release of cure in models.

% Input parameters:

%   day - day of cure release

%   t   – current time state of simulation

function cure = cure(t, day)

  if t >= day

    cure = 1;

  else

    cure = 0;

  endif

endfunction
```

Supplementary Data 9 | SDZR.m

```
% Model of supernatural scenario with resurrection from dead (SDZR)

function dx=SDZR(t,x)

% ---- States/classes ----

% dx(1) - Susceptiple population

% dx(2) - Dead population

% dx(3) - Zombie population

% dx(4) - Removed population

%

% ---- Process parameters ----

% alpha – permanent destruction of zombies by susceptible(s)

% beta – death of a susceptic

% zeta – resurrection of a zombie from dead

% delta – natural death or suicide of susceptible

% lambda – birth of the new individual

%

% Parameters for alpha, beta, zeta adopted from Table 1 of [13].

alpha = 0.9;

beta = 1.1;

zeta = 3.6;

delta = 0.1;

lambda = 0.005;


% Initiate a vector of zeros to update state values.

dx = zeros (4, 1);


dx(1) = x(1)*lambda - beta*x(1)*x(3) - delta*x(1);

dx(2) = beta*x(1)*x(3) - zeta*x(2);

dx(3) = zeta*x(2) - alpha*x(1)*x(3);

dx(4) = alpha*x(1)*x(3) + x(1)*delta;

endfunction
```

Supplementary Data 10 | SEZR_mc.m

```
function dx=SEZR_mc(t,x)

% ---- States/classes ----

% dx(1) - Susceptiple population

% dx(2) - Exposed population

% dx(3) - Zombie population

% dx(4) - Removed population

% dx(5) – Military personel

%

% ---- Process parameters ----

alpha = 0.1;

beta = 0.8;

zeta = 0.9;

delta = 0.02;

lambda = 0.05;

epsilon = 3.0;

mu = 0.2;

phi = 0.2;

psi = 5;

tau = 1.7;

gamma = 0.5;

time_for_cure = 10;


% ---- Process parameters ----

% alpha – destruction of zombies by susceptible(s) (failed encounter for a zombie)

% beta – infection of susceptible by a zombie (failed encounter for a susceptible)

% zeta – disease outbreak (exposed individual turns into a zombie)

% delta – natural death or suicide of susceptible

% lambda – birth of the new individual

% epsilon – cure administration to exposed individual by military unit

% mu – successful cure administration to a zombie by military unit

% phi – failed encounter of zombies by a military unit

% psi – deployment of new units to the site
```

```
% tau – successful attack against zombie by military unit

% gamma – suicide or natural death of exposed individual

%

% time_for_cure - time when the cure is invented and made available


% Initiate a vector of zeros to update state values.

dx = zeros (5, 1);


dx(1) = x(1)*lambda - beta*x(1)*x(3) - delta*x(1) + cure(t,time_for_cure)*x(2)*x(5)*epsilon + cure(t,time_for_cure)*x(3)*x(5)*mu;

dx(2) = beta*x(1)*x(3) - zeta*x(2) - cure(t,time_for_cure)*x(2)*x(5)*epsilon + phi*x(5)*x(3) - gamma*x(2);

dx(3) = zeta*x(2) - alpha*x(1)*x(3) - cure(t,time_for_cure)*x(3)*x(5)*mu - (tau - cure(t, time_for_cure))*x(3)*x(5);

dx(4) = alpha*x(1)*x(3) + x(1)*delta + (tau - cure(t, time_for_cure))*x(3)*x(5) + gamma*x(2);

dx(5) = psi - phi*x(5)*x(3);

endfunction
```