Injury Worsening Risk Modeling and Rescue Emergency Analysis in a Disaster

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ABSTRACT

In a crisis with casualties, while there is no medical intervention, the severity of the injuries increases, and some people may die. Since the number of rescuers is limited, it is necessary to perform a planning and a deployment of this resource on the basis of a risk criterion illustrating the potential increase of the number of casualties at each point of the concerned area. Emergency planning is still a poorly developed science [3]. This paper provides a dynamical model for the number of casualties, inspired from the Verhulst model classically used for biological systems [5], to evaluate this risk criterion as a function of future time. It calculates the evolution of the number of unrescued casualties, the number of dead people, and the number of rescued people, as a function of the number of rescuers. Numerical results are shown.

Keywords

dynamical system modeling, Verhulst, casualties, rescuers, emergency planning, crisis management, disaster

INTRODUCTION

Context

When a disaster has just made casualties, it is crucial that they receive care soon otherwise they may die [1] [2]; hemorrhages must be stopped (e.g. a bleeding femoral artery kills in less than 2 minutes); mouth-to-mouth resuscitation can save if it is initiated within a few minutes; and unconscious victims may suffocate if they are not turned on their side. Wounds involving vital organs may also lead to death more or less rapidly.

Care can be provided by brigades and first aid rescuers in addition to emergency physicians. When the disaster is serious, such rescue teams can be sent from other locations in the region. We propose to improve the emergency planning task [8] with a decision-making support tool performing a quantitative risk analysis (QRA) [4].

The question is to decide where and how many rescuers must be sent, coping with two problems: the total number of rescue resources is limited (at least for a while), and for some locations they are delayed by their way. The planning and deployment tasks must be performed on the basis of a risk criterion indicating the degree of emergency and the potential increase of casualties in each place of the concerned area.

Emergency planning is poorly developed science [3], which is still lacking of mathematical methods. This paper proposes a dynamical system modeling of the evolution of the number of casualties when they are waiting for care. It is derived from biological mathematical models [5], which describe the evolution and equilibrium of mixed populations. These are here the unharmed, the injured and the dead people. Dynamical system modeling is a relevant approach for risk assessment [6].

The studied parameters

The risk is defined here by the forecasted expected additional number of future casualties weightened by the severity of their injuries. The described risk prediction algorithm is applicable at every location in the area of interest (city, region...), considered as a pixel in a map.

The first risk will be modelled as the expected number of casualties that are still alive in the studied location, weighted by the seriousness rate of each one's injury. For risk prediction, this variable must be estimated for a future time t and will be denoted as I_t. The expected number of dead people is denoted by D_t, the rescued are R_t (as for I_t, this is the number weighted by the seriousness). The number of rescuers (brigades, doctors, rescuers...) is B_t. This B_t

parameter is the system input provided by the decision maker. Note that B_t can be the result of a coupled planning and deployment algorithm, since the overall number of rescuers is a limited resource, and there are access delays. These variables are an X_t vector's coordinates:

$$X_t = \begin{bmatrix} I_t \\ Dt \\ Rt \\ Bt \end{bmatrix} = \begin{bmatrix} injured \\ dead \\ rescued \\ brigades \end{bmatrix}$$

This vector is a dynamical system that will be modelled in the proposed approach in the form:

$$X_{t+1} = f(X_t)$$

One can also introduce the internal variable $C_t = I_t + D_t + R_t$ which represents the total of casualties. Of course one must take into account the initial population N_0 by respecting the constraint $C_t \leq N_0$. The other constraint is that none of these variables can be negative. The studied models are discrete-time and t is supposed to be sampled regularly at a meaningful period (i.e. about 10 minutes).

INJURY WORSENING MODEL

Before introducing the rescue effect, in this section we propose the model for injury evolution without rescuers. Only two variables are concerned:

$$X_t = \begin{bmatrix} I_t \\ Dt \end{bmatrix}$$

and this vector must remain in a constrained set K:

$$X_t \in K = \{ (x,y) \in \mathbb{R}^{+2} : x + y \leq N_0 \} \text{ where } \mathbb{R}^{+} = [0;+\infty[.$$

The classical Verhulst model

The classical one-dimensional logistic model, also known as Verhulst model [5], is a tradeoff between the natural Malthusian growth of a population x (exponential model) and the fact that, because of limited resources and inter-individual competition, it cannot be higher than limit N which is called the *carrying capacity*. Its expression is recursive:

$$x_{t+1} = r\, x_t\, (1- x_t/N)$$

where r>0 is a constant parameter. Note that in this case the constrained set is $K = [0;N]$. As soon as $r \leq 4$, the constraint $f(K) \subseteq K$ is satisfied. Thus the model is viable – following the viability theory [6] definition – for any initial state x_0.

The steady state is reached at the equilibrium points $x^* = f(x^*)$. If $|f'(x^*)| < 1$, the equilibrium is stable. In the Verhulst model there are two equilibrium points, detailed in the following table:

	x^*	$f(x^*)$	Stability
Equilibrium 1	0	r	Stable if r < 1
Equilibrium 2	N(r-1)/r	2-r	Stable if 1 < r < 3

Table 1. Steady states of the Verhulst model

Including the number of dead people in the model

The Verhulst model will be extended knowing that the carrying capacity $N=N_0$ concerns the overall number of casualties $C_t=I_t+D_t$. The worsening of the injuries and the death of some seriously injured people results in an increase of the number of casualties, which is proportional to the number of still alive injured people (since the state of the dead people can not worsen more). So in the proposed approach the Verhulst equation is modified as follows:

$$C_{t+1} = C_t + a\, I_t\, (1 - C_t/N_0)$$

where a>0 is a constant. This equation is of type $C_{t+1} = f(C_t,I_t)$ with

$$f(x,y) = x + ay(1 - x/N_0) \text{ and } 0 \le y \le x \le N_0$$

The constraint $C_t \le N_0$ imposes that $a\le 1$. For the system viability the constrained set is

$$K' = \{ (x,y) \in [0,N_0] \times [0,N_0] : y \le x \}$$

One can remark that $f(x,y) \le g(x) = -a/N_0\, x^2 + (1+a)\, x$. It's derivative is $g'(x) = 1+a-2ax/n_0 \ge 0$ for all $x \in [0,N_0]$. So g's upper bound is $g(N_0)=N_0$. That is why $f(K')\subseteq K'$.

This proposed model can be expressed as a function of X_t:

$$X_{t+1} = M\, X_t + Q(X_t)$$

where M is a matrix and Q a quadratic function with parameters such that $\alpha + \mu = a$. α is the worsening rate and μ is the death rate.

$$M = \begin{bmatrix} 1+\alpha & 0 \\ \mu & 1 \end{bmatrix} \qquad \text{and} \qquad Q(x,y) = x(x+y)/N_0$$

Results

An example is shown at figure 1. The initial population is $N_0=1000$ people. At the initial state, there are 1000 injured and 5 dead people. The coefficient of injury worsening is $\alpha = 0.2$ and the death rate is $\mu = 0.05$.

Steady state

The equilibrium is obtained for $I_t = 0$ or $I_t + D_t = N_0$. That means there are no (more) alive injured people. So to make the model more realistic the rates α and μ must decrease as the time increases, as a function of type : $\alpha = \alpha_0/(1+bt^k)$ and $\mu = \mu_0/(1+ bt^k)$.

RESCUE MODELING

Adding the rescuers' effect in the model

One can introduce a new internal variable δ_t which represents the number of rescued people at each time period. It will increase the number of rescued casualties and decrease the number of unrescued ones:

$$R_{t+1} = R_t + \delta_t$$

$$I_{t+t}(\text{with rescue}) = I_{t+1}(\text{without rescue}) - \delta_t$$

δ_t should be proportional to B_t. with a parameter σ representing the number of casualties rescued per rescuer and per time unit. To satisfy the constraints ($\delta_t \ge 0$, $I_t \ge 0$, $C_t \le N_0$) the proposed model is (see fig. 2) :

$$\delta_t = \frac{\sigma B_t I_t}{\sigma B_t + I_t}$$

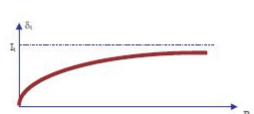

Figure 2. Number of rescued at each time

by including this term in the previous model, we obtain the resulting system

$$I_{t+1} = (1+\alpha)I_t - \alpha\, I_t\, (I_t + D_t + R_t)/N_0 - \sigma\, B_t\, I_t / (\sigma\, B_t + I_t)$$

$$D_{t+1} = D_t + \mu\, I_t - \mu\, I_t\, (I_t + D_t + R_t)/N_0$$

$$R_{t+1} = R_t + \sigma\, B_t\, I_t / (\sigma\, B_t + I_t)$$

Results

In the shown example the number of rescuers was supposed to be constant. That means a team of brigades was sent at the beginning. The last equation of the dynamical system is then : $B_{t+1} = B_t$

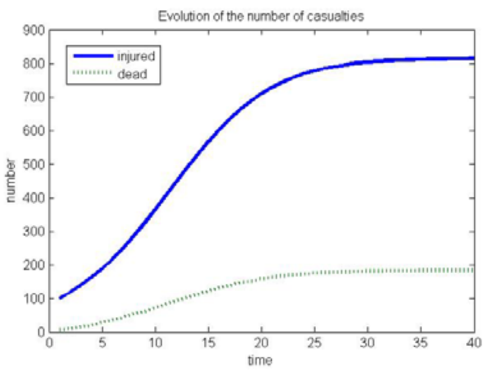

Figure 1. Worsening of the non-rescued casualties state

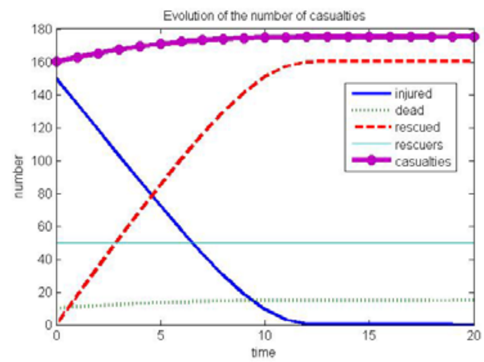

Figure 3. Evolution of the number of casualties in the presence of rescuers

The parameters used in figure 3 are : $N_0 = 1000$; $\alpha = 0.015$; $\mu = 0.007$; $\sigma = 0.01$; there are 180 injured and 10 dead people at the initial state, and 50 rescuers are present.

RISK ANALYSIS

For decision making purpose, the objective is to forecast an evaluation of the casualties worsening risk after a future time, given the observations (the initial number of casualties). The risk value is the difference between overall number of casualties obtained with the model and the initial number of casualties :

$$I_t + D_t + R_t - I_0 - D_0$$

This risk is given in figure 4 as a function of the number of initially sent rescuers. The shown delay is 5 periods. The other parameters are those used in the previous paragraph. This curve answers to the question : “If (only) B rescuers are immediately sent, and if nothing else is done there until a certain delay (i.e. 50 minutes), what is the risk of increase of the number of casualties ?”.

This curve shows an asymptotic behavior, meaning that it is not useful to send too much rescuers. It also provides bounds for the number of new casualties, that can be more easily used to solve the problem of planning and deployment of rescuers on a wide area.

CONCLUSION

We have proposed a mathematical model to compute the future evolution on the number of casualties in a disaster. It can be used as a module to compute the forecasted risk of injury worsening as a criterion, and implemented in emergency planning tasks for decision making support.

The shown results are calculated on a validation example, but the model parameters can be adjusted from statistical data. This dynamical model can itself be refined. For example, constraints on the actual number of injured people could be introduced. To make this fully deterministic approach more realistic, one could consider that is describes the expectation of a stochastic behavior ; this would allow to extract other characteristics of the risk (e.g. the variance of the possible worsening of casualties).

With such a dynamical system modeling of the casualties in a disaster, there are also perspectives to go further in the risk mitigation thanks to the Viability Theory [6], [7]. It allows to define for the decision maker some minimal requested boundaries that would insure for example the existence of a strategy enabling to rescue a controlled percentage of casualties.

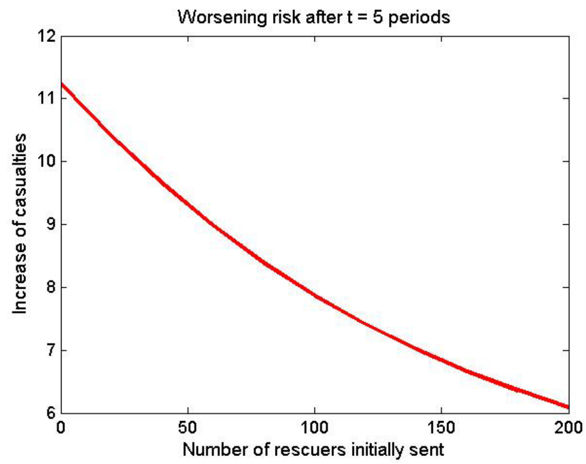

Figure 4. Risk of casualties increase if there are not enough rescuers

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