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ABSTRACT

Discrete-event simulation for health disaster management is a relatively new field. Human victims in these models are usually created with predetermined transitions from one health state to the next, based on a set of triggers which can correspond to treatment procedures performed by physicians, stabilization by paramedics or follow the normal clinical progression of untreated injuries or diseases. In this approach, clinical progression is predetermined and subtle differences are not accounted for. A simulator developed by a team from the Royal Military Academy and the Vrije Universiteit Brussel has successfully implemented a discrete victim model in the past to describe an airport crash scenario. The next step is to generalize this simulator for diverse scenarios where a combination of chemical and physical injuries can happen. To do so, a novel approach to the generation of victims is adopted. In this contribution, the development of a continuous victim model is presented. In this victim model, victims can be assigned both physical and chemical injuries. The dynamic evolution of the health state of the victims follows established injuries models based on trauma registries. Concerning the chemical injuries, a set of existing victim profiles developed by the North Atlantic Treaty Organization are used as a starting set of data, modified for civilian application. The use of a continuous victim model represents a significant advancement over the use of a discrete-based clinical transition model where small changes in timelines of care will have more realistic impacts on the victim's health states. To the best of our knowledge, this is the first time that a continuous victim model is used for disaster management simulations.

INTRODUCTION

The goal of discrete-event simulation of mass-casualty incidents is to test, optimize and develop best practices for medical care in order to save as many victims as possible. In these systems, the victims are the core of the simulator logic. Modelling the health state of victims is very complex due to the unpredictability of the clinical progression of injuries, especially when they are severe. The health state can be further deteriorated if multiple injuries are present. In their SIMEDIS simulator, Debacker et al. have developed an approach which considers predetermined clinical conditions for a database of 205 different victims which can either be critically, seriously or lightly wounded (Debacker et al. 2016; De Rouck et al. 2018). The clinical parameters, such as blood pressure, pulse rate, respiratory rate and motor response, are updated according to time. One weakness is that the health state is modified at discrete time intervals and stays constant in between. Another shortcoming is the absence of interactions between predefined victims and their environment (for instance, the exposure to a chemical agent or new injuries). In order to generate more realistic and dynamic victim profiles, a continuous description is more convenient and flexible. It is the aim of this contribution to present a continuous health state model to be implemented in the SIMEDIS simulator in a later contribution. The model will be applied in a new scenario involving a chemical attack in a metro station where a crowd movement occurs due to the panic. Hence, the type of injuries includes both chemical and physical injuries. Firstly, the model equations in the case of physical and chemical injuries are presented. The second part shows some victim examples with both chemical and physical injuries.

CONTINUOUS HEALTH STATE MODEL

In order to characterize the victim health state, a score was developed based on clinical parameters routinely used in prehospital care, called the SimedisScore (SS). The score is calculated as the unweighted sum of five subcategories, each subcategory consisting of five possible values (0 to 4), with lower values signifying worse states. The categories are chosen based on the parameters currently measured in prehospital medical care and based on existing scores (Sacco et al. 2008, Champion et al. 1989). These established parameters are Glasgow Coma Scale, heart rate, respiratory rate, systolic blood pressure and oxygen saturation. Boundaries are based on the existing scores for the first 4 parameters. Oxygen saturation is added for its ease of measurement, but also because it allows for more possibilities in modelling non-traumatic victims. Concerning oxygen saturation, we chose to adapt the categories based on Raux et al. (Raux et al. 2006).

Military sources already have created and published a set of discretely evolving victim profiles for organophosphate chemical warfare agents. These profiles are converted for use in our simulation model by following a set of simple rules created to assign a value for each of the score categories based on the descriptions provided in AmedP8(c) (Curling et al. 2010).

In order to use this new SimedisScore as reference for victims' health states, a continuous evolution law is needed both for physical and chemical injuries.

Physical Injuries

There are three possible evolutions that can occur to a victim's health state caused by physical injuries: degradation, stabilization or recovery. Additionally, one can define a decrease rate and a delay time after which the degradation starts. In 1825, Benjamin Gompertz proposed an exponential function to describe the mortality rate versus age (Gompertz 1825). The Gompertz function G has the following form for the mortality versus age (here versus time):

$$G(t)=ae^{-e^{(b-ct)}} \qquad (1)$$

a being an asymptotic value, b being the shift in time and c being the rate of decrease (if c is negative).
The Gompertz function will tend to 0 if both b and c are negative and to a if b and c are positive. The Gompertz function was generalized by Ahuja and Nash (Ahuja and Nash 1967) and recently by El-Gohary et al. (El-Gohary et al. 2013). In the latest reference, the generalization of the Gompertz function allows the definition of a survival function. Survival functions are widely used in the medical and biostatistical literature and allow for instance to characterize the outcome of treatments and is very macroscopic in nature (Dempsey and McCullagh 2018). In the frame of the SIMEDIS simulator, the victim health state model is microscopic but needs to include a modification for victims with moderate or minor injuries to survive. Without this possibility, the function from Equation (1) can only represent a dying victim or a victim that keeps a constant SimedisScore value (which doesn't capture any degradation to the health state and would be less realistic).

The modification with the survival function is important to permit the victim to stay alive if, for instance, it has survivable injuries. It has the following definition (GG for Generalized Gompertz, renamed as the SimedisScore (SS) function caused by physical injuries (hence the Phys. suffix):

$$GG(t) = SS_{Phys}(t) = a - (a - ae^{-e^{(b-ct)}})^{\gamma} \qquad (2)$$

Where γ is a positively defined shape parameter. We propose to use such a function as a basis for the victim health state evolution. The victim death occurs when the SS function reaches 0. The maximum value of SS(t) is 20 which corresponds to a fully healthy individual (a sum of the five physiological parameters set to 4 each). Figure 1 presents different combinations of parameters for the $SS_{Phys}(t)$ function.

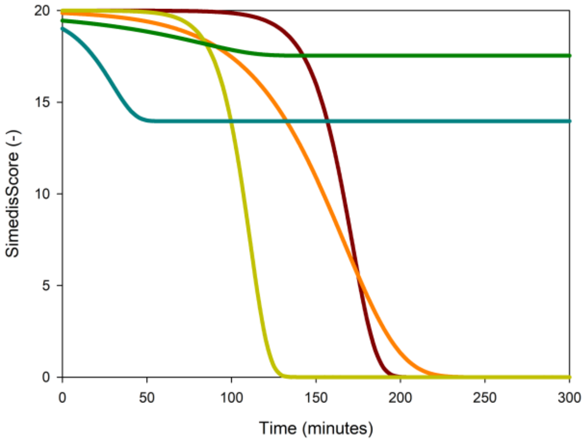

Figure 1: $SS_{Phys}(t)$ function for various parameters (a is always set to 20). Red (b=-12, c=-0.07, γ=1); orange (b=-5, c=-0.03, γ=1); yellow (b= -10, c= -0.09, γ=1); green (b= -5, c= -0.5, γ=0.3); blue (b=-3, c=-0.09, γ=0.6).

Analysis of the victim profiles created by Debacker et al. showed that clinical evolution of the SimediScore in trauma victims follows an asymmetrical sigmoid function with a plateau phase and followed by a progressive deterioration. From clinical experience in trauma care, we often find a terminal compensatory effort of the human physiology. All these factors can be included in the Gompertz function. The choice of the Generalized Gompertz function was also motivated by its simplicity, only consisting of four variables, and *a* being a constant for this application.

The link between the victim's age and the injuries is made via both the b, c and γ parameters. One can show that the SS function (when γ=1) will approach zero at a time t_{death} of approximately (b-e)/c where e is Euler's number. The t_{death} is calculated based the Injury Severity score (ISS). The link between ISS and time of death has been studied repeatedly in the literature and data is readily available (Hussain et al. 2020) (Abdul Raoof et al. 2019) (Sahu et al. 2021) (Clarck et al. 2014).

The ISS is an injury severity score determined by the body location and severity of the injuries (abbreviated injury scale (AIS)) (Petridou et al. 2017). Based on analysis of multiple publications we propose the following exponential relationship between ISS and t_{death}.

$$t_{death} = 43500\ ISS^{(-1.95)} \qquad (3)$$

It should however be noted that there are severe limitations to this formula: there are no datapoints for low ISS numbers as mortality is typically very low and outside the scope of the studies linking ISS to time of death. The source of this data is mainly post-mortem research on motor vehicle incident victims in rural regions. Rural prehospital care is frequently associated long driving distances, both to and from the accident, and represents better the untreated clinical evolution of a victim. A similar study by Cros et al. showed significantly higher survival times for homicide victims in the Paris region of France. (Cros et al. 2013)

These datasets have little data on the lower ISS scores, because these are usually non-lethal. We assume victims with an ISS of less than 10 will survive at least 24 hours for the modeling duration. For those victims we assume a gradual decrease in SS over 60 minutes, based on our internal database of expert opinion derived victim profiles, to a SimedisScore between 17 and 20 based on the victim's ISS.

To compensate for the victims age and decreased compensatory capacity, a bathtub curve is used to set c (faster decrease for children (age <12) and older people (age > 70) with a constant value in between). Consequently, all parameters are based only on age and ISS score. Additionally, victims with ISS higher than 25 have a faster decrease with a different bathtub curve parallel to the one for lower ISS values.

Chemical Injuries

Equation (2) models the evolution of the victim's health state based only on physical injuries since the ISS (of equation (3)) is defined for physical injuries. To consider chemical injuries, an additional term is added to Equation (2) depending on the inhaled dose of a toxic chemical agent (Sarin (GB) is used as a test case).

$$SS_{chem+phys}(t) = SS_{Phys}(t) + \Delta Chem(t) \qquad (4)$$

$\Delta Chem(t)$ being a function to be determined affecting the evolution of the health state of the victim after inhalation of an organophosphate chemical warfare agent. The effect of the chemical injury and physical injury are linearly combined in the health state. To define the chemical modification function, the AmedP-7.5 and AmedP8(c) NATO standard progression of symptoms are used as a reference (Oxford et al. 2016, Curling et al. 2010). A fit is performed on the datapoints of 6 different chemical profiles depending on inhaled dose. In addition, the clinical parameters are converted to SS changes. Except for profile 6 which can be fitted with a Generalized Gompertz function, the 5 other profiles are well approximated by a modified χ^2 distribution with the following mathematical expression (with the addition of a shape parameter γ).

$$\Delta Chem(t) = A + ((\alpha/(2^{k/2}\Gamma(k/2))t^{(k/2-1)}e^{-\beta t/2})^{\gamma} \qquad (5)$$

A, α, β, k and γ are AMedP8(c) profile specific parameters determined by a least-squares fitting method. Γ is the complex gamma function.

A last modification was introduced concerning mortality and injuries. Equation (3) estimates a "time of death" from the ISS resulting from a combination of injuries in a cumulative manner. Only few injuries are lethal such as a flail chest, a hydropneumothorax, major hemorrhage or traumatic asphyxia but a sum of non-lethal injuries are generally not fatal although the combined AIS scores of these injuries can result in a high ISS resulting in an early death. To account for this effect, the γ parameter is only set to 1 if at least one lethal injury is present.

VICTIM EXAMPLES

To illustrate the model, in this section, some victims are described with their health state evolution from the specific scenario of a chemical attack in a metro station. The victim examples below are generated in the simulator as follows.
Injuries and sarin doses are set in the SIMEDIS simulator based on different modules. One of these modules is a gaussian plume physico-chemical model of sarin diffusion, based on the victims' positions. An evacuation module is implemented to set the victims positions with a combined social force model (Wan 2014, Zou 2020). Concerning physical injuries, a distribution of severely, moderately and mildly injured victims are generated from a database of injuries ranked by severity (AIS scores) depending on the victim local densities in the metro station during the evacuation. Although age has a negative impact on the rate of deterioration of injuries, the ISS score and total inhaled doses play a more important role towards shifting the time of death and affecting the survivability of the victims.

Victim 1 aged 58 has a cervical fracture with transection (AIS 5, lethal) and a sprained shoulder (AIS 1) all caused by a fall from stairs while exiting a metro station.
The victim has an ISS of 26 resulting from Equation (3) leading to an estimated time of death of 70 minutes (based only on physical injuries). In addition, the victim was exposed to GB (Sarin) with a total inhaled dose of 6.49 mg-min/m³ falling into the AMedP8(c) third profile. GB was present in the metro as part of a terrorist attack. The added nerve gas inhaled deteriorates the victim health parameters even further shortening the lifespan in absence of treatment to 54 minutes. Following Equations (2) and (4), the plotting of the victim health state is as follows:

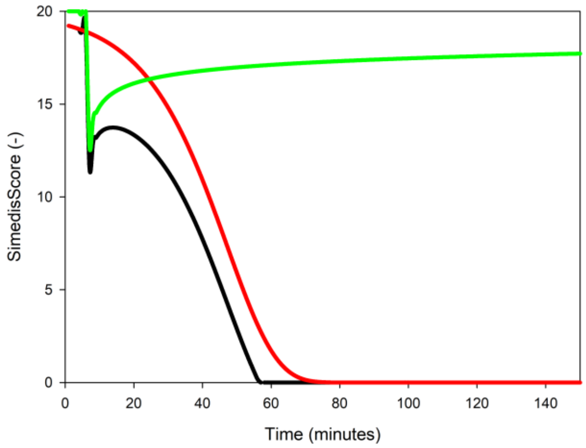

Figure 2: Health state evolution of victim 1. In black the combination of physical and chemical injuries, in green the chemical injuries evolution and in red the physical injuries evolution.

The red curve shows the health state evolution based only on the victim physical injuries (Equation (2) with the following parameters: b = -3.3, c=-0.07, γ = 1). The green curve is the evolution of symptoms of the AMedP8(c) third profile (Curling et al. 2010) with Equation (5) and the parameters A= 1, k=1.4, α=15, β=1/350 and γ=0.92. We suppose that the onset of symptoms is 5 minutes after inhaling the chemical agent. The resulting combination from Equation (4) is shown in black. The health state evolution corresponds to an untreated victim left alone. It is important to stress that, once the medical personnel will treat the victim, an improvement function will increase the value of the SimedisScore dynamically and prevent the victim from dying. The improvement can be in the form of an increasing function or a change in the γ parameter to a value between 0 and 1 (1 not included). More details about the treatment model will be described in the next version of the SIMEDIS simulator. In addition, the ISS score is comprised of a sum of squared AIS scores which are fixed for each type of injuries depending on their severity. A scale from 1 to 5 is assigned to injuries. An example of a severe injury is a hydropneumothorax, flail chest or unstable lumbar fracture, which are deadly if left untreated.

Victim 2, aged 77, has an ISS of 18 caused by a tension pneumothorax (AIS 4, lethal), a sprained wrist (AIS 1), an ankle sprain (AIS 1) combined with a total inhaled dose of 17.28 mg-min/m^3 of GB. It falls under the 5th profile of the AMedP8(c) (Curling et al. 2010). As for victim 1, the chemical effect of profile 5 deteriorates the health state and the time of death of the victim is shifted from 146 minutes down to 107 minutes.

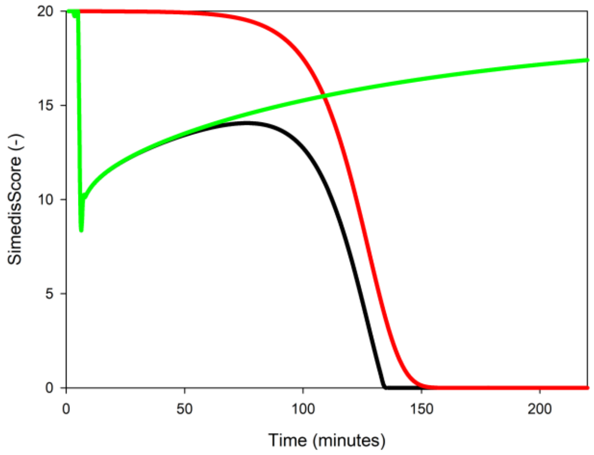

Figure 3: Health state evolution of victim 2. In black the combination of physical and chemical injuries, in green the chemical injuries evolution and in red the physical injuries evolution.

The physical injuries curve (in red) decreases less sharply than victim 1 who had an ISS of 26. The following parameters were used for the generalized Gompertz function (b = -4.07, c=-0.04, γ = 1) and for the chemical part A= 0, k=1.85, α=20, β=1/75 and γ=0.99.

The third example, victim 3 is a 59-year-old with a pelvic fracture (AIS 2) and rib contusion (AIS 1) resulting in an ISS of 5. He inhaled a dose of 0.8 mg-min/m^3 of GB resulting in an AMedP8(c) profile 2 of chemical symptoms (Curling et al. 2010). These symptoms wear off after 154 minutes. The low ISS is not life-threatening and the SS tends to a plateau of 17.5 until treatment is given to the victim. Following the discussion about Equation (3), this victim example has its SS decrease after 60 minutes with the following parameters: for the generalized Gompertz function b = -8, c=-0.03, γ = 0.3 and for the chemical part A= 0, k=8, α=0.07, β=1/14 and γ=1. If the victim is not treated after 1 hour, it starts decreasing its health parameters by about 10% (SS around 17.5) but remains relatively fine and not in danger.

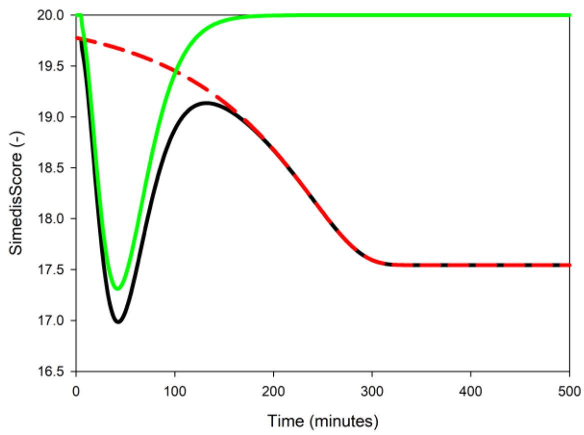

Figure 4: Health state evolution of victim 3. The combination of physical and chemical injuries is presented in black; the physical injury evolution is in dashed red (for better visibility) and the chemical injuries evolution is in green. Past 154 minutes, the chemical effects have completely disappeared.

According to the AMEDP8(c) progression of symptoms, past an inhaled dose of 30 mg-min/m^3 for the military population, sarin exposure is 90% deadly. The symptoms include unconsciousness, prostration and flaccid paralysis (Curling et al. 2010). For the general population we assume to shift the maximum dose to 20 mg-min/m^3. The time of the onset of symptoms is dose-dependent and in the case of the 6th and last profile, death occurs after 25 minutes if no antidote is applied (atropine and oximes).

As a last example, victim 4, aged 28 has received a dose of 24.87 mg-min/m^3 putting it into the lethal 6th profile. The only way to save the victim is in applying antidote before the small 25 minutes window.

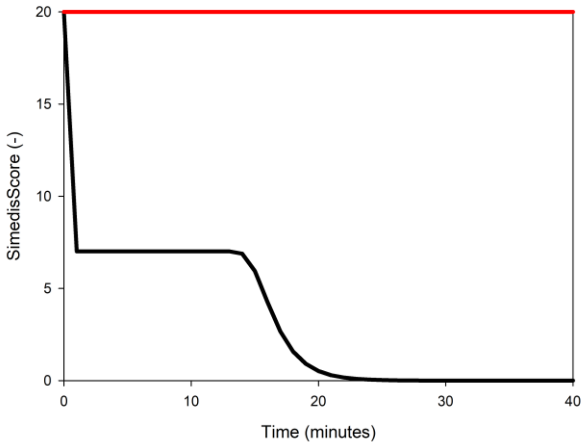

Figure 5: Health state evolution of victim 4. The combination of physical and chemical injuries is presented in black which is only due to the chemical injury (the physical injury curve in red as the ISS is 0). The lethal sarin dose will result in the victim death after only 25 minutes if no antidote is given. The 6th profile fit is a generalized Gompertz

function (b= 13.6, c=0.88 and $\gamma = 0.65$) but the asymptotic behavior is reversed as both b and c are positive.

The list of examples is non-exhaustive and illustrates the different situations that can be modeled by the continuous victim model in the case of physical, chemical and combined injuries. It permits to generate any number of victims without relying on a fixed set of victims from a database which is computer intensive due to constant access to evaluate the predetermined health state of a victim at a given time. Instead, computing an analytical formula is few orders of magnitude faster.

CONCLUSION

In this contribution, a continuous model to describe the health state evolution of victims in a mass-casualty setting has been presented based on an existing dataset of clinical transitions for physical injuries and refined with the possibility to add chemical injuries to a set of physical injuries. The equation for physical injuries is based on a generalized Gompertz function. The parameters of this function are derived from the victim Injury Severity Score and age. The contribution of chemical and physical injuries is linearly combined and cross-interactions are neglected. The evolution of the victims' health states does not include the treatment and antidotes applications, which in essence can drastically modify the mortality outcomes. More details about this model will be described in the next SIMEDIS research contribution with the CBRN scenario especially concerning the modifications to equations for different types of treatments.

FUTURE RESEARCH

The presented model shows a generalization of the discrete-event victim model used in previous simulations where all victims had predetermined health state progressions set by subject matter experts (Debacker et al. 2016; De Rouck et al. 2018). The flexibility of our new approach resides in the fact that hundreds or thousands of victims can be generated very quickly at simulation runtime, and it is very computer efficient. The adapted victim model will be included in version 3.0 of the SIMEDIS simulator and used in future simulation studies including CBRN and battlefield scenarios.

Future research possibilities are improving the quality of the assumptions used in the clinical evolution of treated and non-lethal victims, and adding the interaction between the injured regions composing the ISS score.

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