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DISCRETE-EVENT SIMULATION OF THE DISASTER RESPONSE IN THE AFTERMATH OF A COORDINATED UNMANNED AERIAL VEHICLE STRIKE IN AN URBAN AREA

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ABSTRACT

The increasing use of suicidal and explosive Unmanned Aerial Vehicles (UAVs) poses a significant threat in both battlefield and urban environments, as evidenced by recent events in Ukraine. This study employs the SIMEDIS Simulator to simulate a triple UAV strike in Brussels City Centre, comparing two evacuation strategies: "Stay and Play" versus "Scoop and Run." The simulation incorporates medical facility locations, bed capacities, and evolving patient conditions. Findings highlight the importance of rapid patient transport to surgical facilities, emphasizing the effectiveness of the "Scoop and Run" approach alongside timely medical interventions and adequate blood supply. Challenges such as hemorrhage control and managing multiple disaster sites are also discussed. This study underscores the necessity of efficient evacuation protocols and medical responses to mitigate casualties in urban disaster scenarios involving UAV attacks.

1 INTRODUCTION

Assessing and establishing best practices in disaster response are important endeavors for safeguarding and asserting resilient Emergency Medical Services (EMS) Systems. It also becomes mandatory as the world is facing new threats from state and non-state actors. As a result of the aggression of Ukraine by Russia, we must be aware that escalation to other countries has become a possibility. The planners, decision-makers and medical responders must be ready for the worst, especially from a medical perspective because the number of casualties expected from a direct conflict with a near-peer adversary will exceed the current capabilities. Disaster preparedness has received a lot of attention following the catastrophic terrorist attacks during the recent years where large cities were targeted (Carli et al. 2003; De Cauwer et al. 2024; Gates et al. 2014; Timbie et al. 2013). Enemy disruptive capabilities towards urban centers include the over-reliance on guided or unguided Unmanned Aerial Vehicles (UAVs) which include suicidal ones named loitering munitions, cyberwarfare, and the use of air raids. To determine best practices and quantify mortality resulting from Mass Casualty Incidents (MCI), computer simulation is a cost-effective and thorough avenue (Glasgow et al. 2018; Heller et al. 2023; Igra et al. 2024; Niessner et al. 2018; Wang et al. 2012). MCI preparedness applies both to civilian and military domains, where they can occur and will especially be encountered in the context of Large-Scale Combat Operations (LSCO) (Biswas et al. 2023; Marsh and Hampton 2022; Remondelli et al. 2023; Tien and Beckett 2022).

The excessive use of loitering munitions in Ukraine results in a large number of injured and killed civilians in cities even though they are usually employed to target infrastructure (Office of the High Commissioner for Human Rights 2023). When launched in swarms, air defenses are the only shield that populations have, and it is sometimes not possible to intercept them all. The use of supersonic missiles keeps the air defenses busy while smaller and slower UAV can pass through the net and do damage. Explosions from loitering munitions induce blast (barotrauma), penetrating, and amputating injuries which can result in major hemorrhage. Hemorrhage is the leading source of preventable mortality in MCI (Kauvar et al. 2006; Neeki et al. 2021). At a close distance from the blast location, the density of projected fragments is so large that it becomes one of the main injury mechanisms next to blast lung (Cross et al. 2016; GICHD 2017; International Committee of the Red Cross 2022; Nunziato et al. 2021). Research contributions by the authors have led to the design of several MCI scenarios using the Simulation for the Optimization and Assessment of Medical Disaster Management (SIMEDIS) simulator (Benhassine et al. 2023a; Benhassine et al. 2022; De Rouck et al. 2023; Debacker et al. 2016).

In this stochastic discrete-event simulation (DES) model, we accounted for the real Medical Treatment Facilities (MTFs) with their own unique capabilities and capacities, and simulated the EMS response, triage, treatment, and clinical progressions of each patient affected by the threats. MCI scenarios researched shared one key hypothesis: namely, there was only one disaster site. Unfortunately, coordinated attacks have occurred in city centers and with these, responders face enormous difficulties and challenges as to resource allocation. Is it acceptable to send everything you have, or keep some in reserve for future threats? Can you safely reach the sites? Have the threats been neutralized? Is the site free of all contamination? We tried addressing some of these questions using SIMEDIS in the past for a single threat (Benhassine et al. 2023a) and intend here on generalizing to a more complex system, i.e., a triple attack.

2 MATERIALS AND METHODS

2.1 Explosive UAV Effects Modeling

The first stage in modeling the MCI response is to create the threat and geolocate victims. Computational models of conventional weapon systems have been developed for the purpose of mission planning and in estimating explosive effects for a myriad of conventional weapon systems (Driels 2020a; Driels 2020b). Specifically, explosive UAV effects have been reported in the literature (Heszlein-Lossius et al. 2019). The Shahed 136 has received particular attention in the current conflict in Ukraine. With a payload equivalent to a single 155mm artillery shell (with an approximated max payload of 50kgs)(MilitaryToday.Com 2023), the explosive effects are devastating. The International Partnership for Human Rights (IPHR), the Independent Anti-Corruption Commission (NAKO), Truth Hounds, and Global Diligence LLP provide 10 case studies for the use of drones in Ukraine (the International Partnership for Human Rights (IPHR) et al. 2023). Explosive patterns from a loitering munition can be assumed to have a circular shape because the fragments are symmetrically arranged around the warhead. This is a modeling assumption because the angle of impact can affect fragment spread around the blast area. Taking this munition as base for this study we define our assumptions (Table 1) for the explosive effects and outcome.

Table 1: Parameters for the modeled explosive UAV explosion.

Number of fragments	~1000
Payload	36-50 kgs
Lethal area	800 m²
Lethal radius	16 m
Number of casualties per hit	30

Note that the number of casualties depends on the local pedestrian density, and we do not assume the position of the victim and if they are wearing body armor. We simply suppose that the victims are unprepared and surprised to avoid unnecessary modeling complexity. We model three separate locations for the strike in an urban area. Brussels is taken as a test case since it was used in previous research and the MTF layout is already set. The strategic importance and justification of the strike in the city is irrelevant in this hypothetical scenario.

2.2 Patient Injury Model Resulting from UAV Explosions

Injuries from explosions can be categorized in blast, penetrating injuries, and burns (Champion et al. 2009; Benhassine et al. 2023a). Lung injuries ("blast lung") are caused by the sudden change of pressure during the explosion called "blast wave"' and can induce lung injuries, lacerations and perforations of the digestive systems, tympanic membrane rupture (ear loss). This mechanism is the primary source of mortality for explosions. The high energy supersonic wave is followed by the "blast wind" which expels and carries objects and persons with it producing blunt, crush and penetrating traumas. In the case of loitering munitions with a large number of fragments, injuries from fragments close to the impact (because of the substantial number of fragments with large kinetic energies) become an important cause of lethality. Defining an injury profile resulting from a UAV blast with fragmentation can be seen as a combat penetrating injury from an improvised explosive device (IED) for which conventional civilian trauma scales, like the Abbreviated Injury Score (AIS) and Injury Severity Score (ISS) first used to characterize motor vehicle accidents are not always the best indicator, especially for high-explosive designs with injuries spanning multiple areas of the body (Lawnick et al. 2013). Lawnick argues that the ISS, conventionally used to characterize physical trauma has some caveats in this case (Champion et al. 2010; Lawnick et al. 2013).

The management of such injuries are classified in order of importance by hemorrhage control, airway management, blood transfusion and damage control surgery (DCS) (Shackelford et al. 2022).

The patients' health status evolution model in SIMEDIS is comprised of a set of analytical equations based on 3 parameters for physical injuries and a separate treatment of Chemical, Biological, Radiological, and Nuclear (CBRN) related injuries if present (Benhassine et al. 2023b). In the current model, there is a separate consideration for hemorrhage from fragments, and we consider blast injuries to be embedded inside the physical injuries. The estimated time of death of patients in the simulator is based on the ISS (defined as a squared sum of three worst injuries with their AIS). The widespread reporting of this metric in past MCIs justified its adoption, but as mentioned, it may be a poor surrogate for combat injuries resulting from blast and penetrating fragments as the location of the injuries can span multiple regions especially for high-kinetic energy explosions (Lawnick et al. 2013). To determine the patient's initial injuries and their evolution, we propose to follow the same approach as the artillery model, since a single UAV explosion is supposed equivalent to a 155mm explosion (Benhassine et al. 2023a). For each explosion, based on distance, patients' military combat injury scores (MCIS) are determined and linked to a projected time of death without any medical intervention. This results in a patient distribution which can be sorted by severity (or initial triage category). On top of this score, an algorithm determines if the patient is incapacitated (which in the case of civilians is equivalent to unable to walk/move by themselves) and/or hit by a fragment. Patients near the blast have an increased likelihood of immediate fatality as well as a higher probability of sustaining fragment-related injuries. This probabilistic model of lethality indicates that individuals located farther from the blast epicenter can still be fatally injured by fragments, albeit with a reduced probability. Modeling precise fragment distributions and effects on human targets is challenging (for instance following the approach of Catovic (Catovic and Kljuno 2021)). Our modeling assumptions neglect these considerations but include simple relationships to estimate injuries versus distance from the blasts. In SIMEDIS, the health state evolution is measured by the "SimedisScore" (SS). This metric is a merging of 5 prehospital scores converted to a scale of 0 to 4 each, resulting in a SS bounded from 0 to 20. A SS of 0 equals death in the model, and a fully healthy individual is supposed to have a score of 20 (a sum of 5 scores at 4). In our previous artillery model, we used the following relationship to establish the patient health evolutions:

$$SS(t) = 20 - (20 - 20 * \exp^{(-\exp(b - c*t))})^{\gamma} \quad (1)$$

γ is a shape parameter which values 1 if the evolution is lethal (in which case SS(t) tends to 0) and is comprised between 0 and 1 if the patient should not die (and the SS(t) will then converge to $20\text{-}20^{\gamma}$). The parameters b and c define the evolution of the SS versus time and are tied together by the following relationships (the time of death is defined when SS values 0) where e is Euler's number:

$$t_{Death} = \frac{\mathrm{b-e}}{\mathrm{c}}$$

Fitting from available datasets of ISS versus time of death permitted us to estimate that $t_{Death} = 43500ISS^{(-1.95)}$. However, the ISS should be replaced by the MCIS scale as previously mentioned. Therefore, we propose retaining this definition but substituting the ISS with the MCIS. This change does not affect the outcome because we lack datasets for clinically predicting the time of death from blast and penetrating injuries. Nonetheless, this methodological shift is crucial for future developments. For fragment hit probability and incapacitation probability, we used the following relationships derived from an analytical model described in a report by Dullum (Dullum 2010).

$$P_{hit} = 1 - \exp(-NA/4\pi r^2)$$

$$P_{incap} = \exp(-\pi r^2/A_l)$$

Where N is the number of fragments per detonation, A is the exposed body area (set to 0.5m² conventionally used for humans), r is the location of the patient respective to the blast location. For incapacitation, A_l is the lethal area. A value of 800m² (a lethal radius of 16m) for the lethal area was used for a single UAV carrying a warhead of 40kgs of explosives. The MCIS versus distance relationship was set as follows:

$$MCIS = \max\left(75, \frac{2*75}{r}\right)$$

With r the distance in meters from the blast epicenter. This number was based on the fitting curve determined in the previous artillery model in SIMEDIS and discussed with SMEs. The results of three explosions from the UAVs result in 50 critically injured (T1) patients and 40 severely injured (T2) patients in the beginning of the response, out of which 59 have received fragments, and 15 are incapacitated. The mean MCIS is 37.8. Mean time of death is 86.42 minutes, and 18 are set to die within the first 10 minutes after the explosions due to major hemorrhage.

2.3 Discrete-Event Simulation Model of the Disaster Response in the Aftermath of the UAV Strike

Implementation of the scenario was performed within the SIMEDIS simulator, adapted specifically for multiple sites, and entirely coded in the Julia programming language (Bezanson et al. 2014). We represented the MTF layout surrounding Brussels as has been done for a Sarin release scenario in a metro station and for an artillery strike in a rural area (Benhassine et al. 2022; De Rouck et al. 2023; Benhassine et al. 2023a). We used Geographical Information System (GIS) modeling for matters of patient localization and ambulance routing from the Point of Injury (POI) towards the MTFs. In the case of the Stay and Play scenario, all patients transited through a single MTF (the Forward Medical Post (FMP)) before being transported to the other MTFs. This is a requisite step used by EMS responders in current doctrines where doctors and nurses from other locations are sent close to the disaster site (SPF Santé publique 2017). The use of Stay and Play versus Scoop and Run is a matter of debate (Neeki et al. 2021;Smith and Conn 2009). Scoop and Run has been shown to result in less preventable mortality in urban areas (Smith and Conn 2009) which is a result that we have confirmed for past scenarios in SIMEDIS.

The simulation pipeline starts with the creation of patients based on the threats' locations. Each patient has an evolving health status, a triage category, and a projected time of death. Then, after a set alert time, EMS resources arrive at the blast site or FMP based on their travel times, with origin as EMS posts. Once on-site, Search and Rescue firefighters (S&R) agents evacuate incapacitated patients based on advice from the Medical Director arrived at a designated Casualty Collection Point (CCP). A quick preliminary triage is performed on-site both to determine order of evacuation (called PreTriage) and at the CCP to determine who needed transport first. The priority is based on current SimedisScore and initial triage category if known. Each patient is represented by a process within the SimJulia library. Besides the FMP and CCP, all surrounding hospitals are considered as Role 3 equivalents (R3). R3 being a definition encompassing surgical and specialized care defined in the AJP-4.10 NATO document (NATO STANDARDIZATION OFFICE (NSO) 2019) and was introduced in the artillery strike scenario and subsequent research for SIMEDIS (Benhassine et al. 2023a).

3 RESULTS

3.1 Scenario and Blast Locations

The modeled scenario unfolds as follows: Belgium has been invaded by enemy forces seeking to advance towards the capital city. In the evening, multiple Shahed 136 drones are launched on the Brussels City Center and the population is caught by surprise. Many try to seek shelter, unaware of the target locations. Air defenses around the city manage to neutralize a few drones from what seems like an all-out strike to instill fear on the civilians. The neutralized drones hit uninhabited zones and result in no casualties, but three manage to penetrate the defenses and hit the city at three separate locations. The first location is the Grand Place of Brussels, the second one hits the King Baudouin Stadium where people are sheltering and a third drone crashes in front of the NATO Headquarters. The three strikes result in a total of 90 casualties (30 per strike). The graphical representation of the scenario in SIMEDIS is displayed in Figure 1. This image is a snapshot from an animated HTML file replaying the disaster from the threat towards the end of the simulation (up to the R3 discharge) and generated as part of the simulator's outputs.

Figure 1: Initial placement of the strikes and resulting victims. Strike 1 is in the King Baudouin Stadium (top left), strike 2 is situated in front of NATO HQ (to the right), and strike 3 is in the Brussels' Grand Place

(bottom left). Icons representing Casualty Collection Points (CCP), and Role 3 (R3) medical treatment facilities are shown. Circles represent casualties. Close-ups for each disaster site are displayed, with T1, T2, and dead casualties.

3.2 Arrival of EMS Services and Routing

Once the patients are located, a route network connecting all surrounding MTFs to the blast sites is computed and serves as pipelines for the arrival of EMS services. A visualization of this network is provided in Figure 2. The traffic is accounted for indirectly by dilating the computed times by a factor of 1.7 from a* algorithmically determined routes with actual estimations from Google Maps. This factor was estimated as an average empirically determined by the Google Maps estimations.

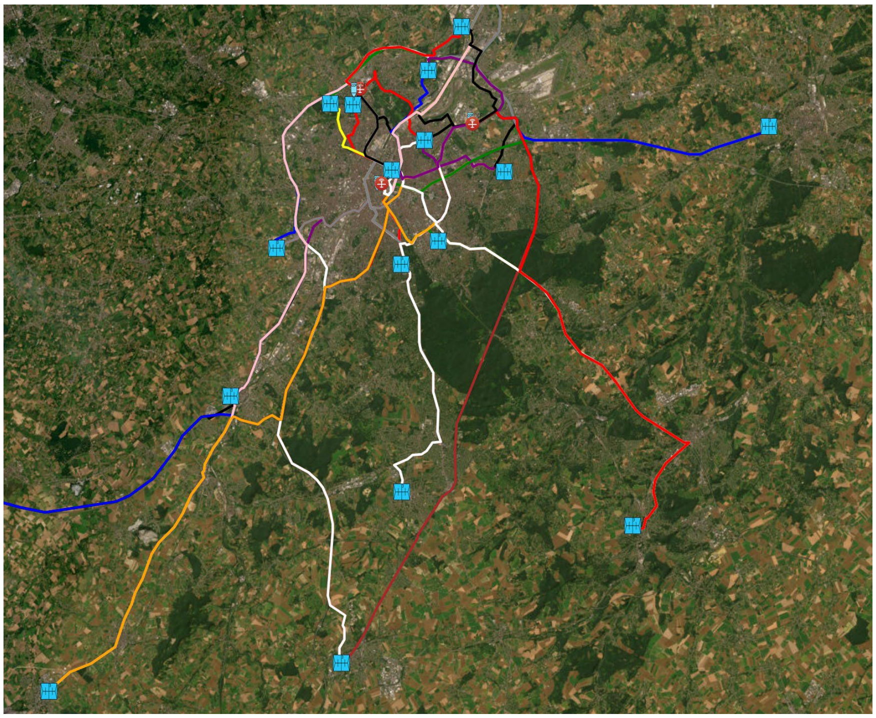

Figure 2: Route network connecting the disaster sites (labeled with a red "drone" icon) to the different hospitals (R3). These routes are the only routes taken by the ambulances to dispatch the victims towards their final care locations, being the fastest routes determined by the a* algorithm.

3.3 Triage, Hemorrhage Control, and Interventions Modeling

First contact to the patients is made by S&R and Mobile Medical Teams (MMT). Both S&R and MMTs are trained in the application of a tourniquet (TQ). Triage is performed on site by a nurse, and at the CCP by a doctor and a nurse. TQ application is modeled in the way that, if successful (based on a 70% probability threshold), the γ parameter in equation (1) is temporally prevented to reach 1. This way, health state for patients with fragments decreases but the victim does not immediately die from hemorrhage. Barotrauma can still kill the victim and major hemorrhage may not be managed solely by a TQ, but we assumed that in 70% of the time it was successful. TQ application is a mandatory step to save patients with fragments because of the lethal time limit. Another assumption is that TQ application, and availability, is a patient's responsibility or that the population in the context of warfare has received training and has access to a TQ or an equivalent device (a belt for instance).

Then depending on evacuation policy, ambulances arriving to the CCP transport the most severely injured patients (T1) either to the closest hospital serving as a hub and being a replacement for a Forward Medical Post (FMP) in the Stay and Play policy or directly to the MTF network based on their capacity per hour in the Scoop and Run approach. In Stay and Play, capacity is disregarded for the hospital acting as FMP where surgery is held and only Damage Control Resuscitation (DCR) is performed in the form of managing hemorrhage, airway, and managing pain prior to transport towards trauma centers. DCS could only be performed at the R3 MTF and not at the FMP, nor CCP. Modeling medical interventions is performed via an adaptation of the SimedisScore evolution (modifying the equation (1) with an added improvement term). The definition of the improvement functions is described in Benhassine (Benhassine et al. 2023a). We assumed that arrival to a R3 hospital implied survival and that deaths could only occur in the prehospital space. In the simulations, all event times were varied by up to 20% using a truncated normal distribution to account for stochasticity and variation in treatment, triage, transport, and arrival times between runs.

3.4 Parameter Space and Key Indicators

The following parameters were varied between simulation replications: TQ application (yes or no); evacuation policy (Stay and Play or Scoop and Run); Pretriage on site for the evacuation of immobile or incapacitated victims (yes or no); hospital distribution policy (closest hospital first (Close First) or random (SpreadOut or SpO)). The main indicator was mortality, another indicator was mean hospital arrival time. The factorial design of the simulations was thus 2^4 for (TQ application x evacuation policy x Pretriage x hospital distribution policy).

3.5 Mortality and Outcome

Results for mortality for the 16 parameter combinations are displayed in Figure 3. Each parameter combination was replicated 10 times, yielding the error bars in the plot.

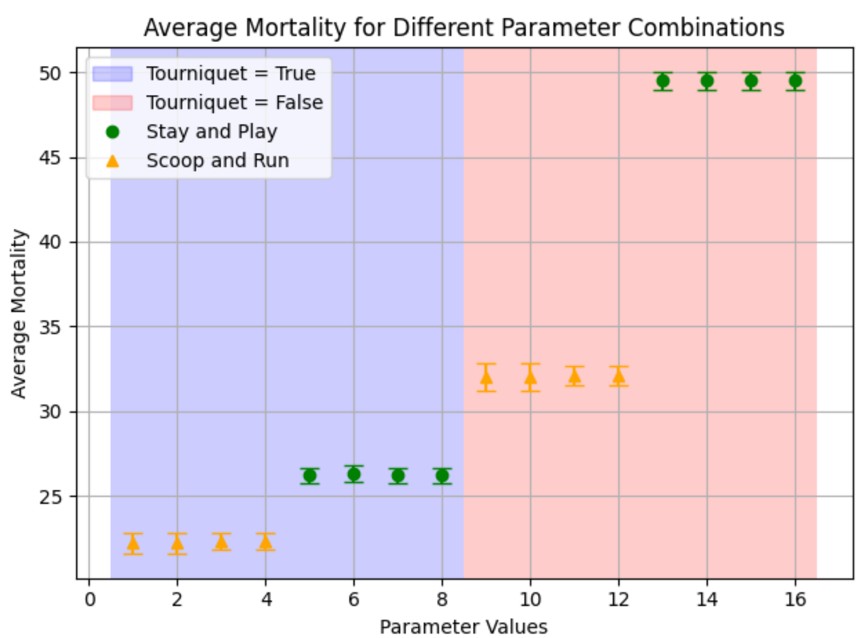

Figure 3: Average mortality outcomes versus parameters (10 replications) with 8 ambulances dispatched per site (24 in total) with standard deviation. The first 8 parameters combinations correspond to a setting where a TQ is used, and not in the last 8. Orange triangles are when the evacuation policy is Scoop and

Run; green circles are Stay and Play. The best outcome is when hemorrhage control measures are employed followed by a Scoop and Run approach to evacuation. Within each set of symbols, parameter variations are pretriage (yes/no) and hospital distribution policy (SpO (random) versus Close First). Multiple Linear Regression (MLR) analysis was performed on the data with results in Table 2.

Table 2: MLR output for 24 total ambulances. Mean mortality is 35.44(±2.27) deaths. R^2 values 0.895.

Parameter	Value	Coefficient	P-value	95% confidence interval
TQ	True	-16.5375	0.001	(-21.01; -12.07)
Policy	S&P	10.7125	0.000	(6.24; 15.18)
PreTriage	True	-0.0375	0.987	(-4.51; 4.43)
HospDist	SpO	-0.0125	0.995	(-4.49; 4.46)

MLR results show a 46.6% reduction in mortality by employing a TQ. With 18 victims expected to die within ten minutes of the explosions without a TQ, mortality reduction is optimistic (almost 100% of victims receiving one survived) but also a consequence of the assumption that TQ application had 70% of success. The other significant parameter of added mortality is the Stay and Play (S&P) approach as evacuation policy with an increased mortality of 30%.

Another indicator was mean arrival time at a R3 MTF where DCS could be performed, and victims were saved. Mortality always occurred in the prehospital setting in our model. Victims were all admitted within 1 hour in the Scoop and Run policy setting but were delayed up to 170 minutes in Stay and Play knowing that they had already received DCR at the FMP. This result was also obtained in another SIMEDIS study evaluating delays of patient arrival to MTFs (Benhassine et al. 2023c). The best outcome is when hemorrhage control measures (TQ) are employed followed by a Scoop and Run approach to evacuation. We see that the delay in arrival to the R3 is one reason Scoop and Run provides better mortality outcomes. MLR was performed on the results and are displayed in Table 3.

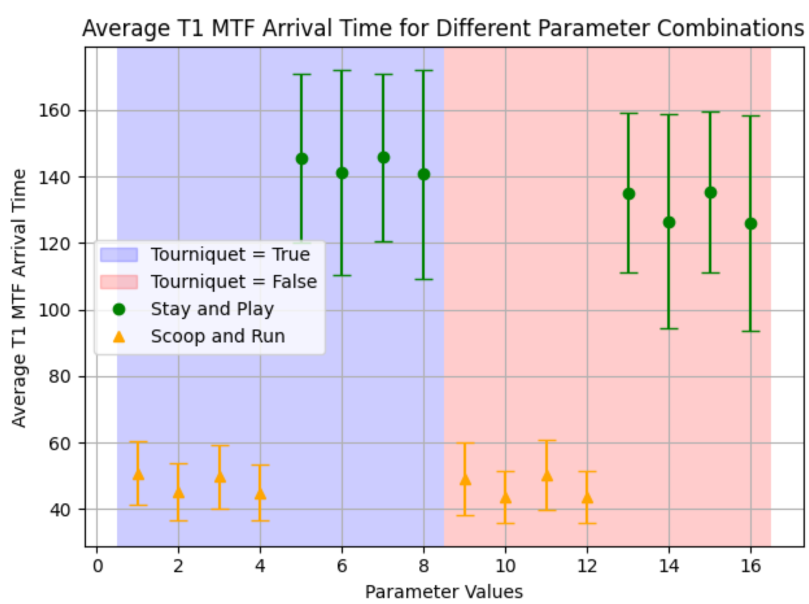

Figure 4: Average R3 MTF arrival times for T1 patients versus parameters (10 replications) with 8 ambulances dispatched per site (24 in total) with standard deviation. The first 8 parameters combinations

correspond to a setting where a TQ is used, and not in the last 8. Orange triangles are when the evacuation policy is Scoop and Run; green circles are Stay and Play. Within each set of symbols, parameter variations are Pretriage (yes/no) and hospital distribution policy (SpreadOut (random) versus Close First).

Table 3: MLR output for 24 total ambulances. Mean MTF arrival time is 40.62(±2.04) mins. R^2 values 0.995.

Parameter	Value	Coefficient	P-value	95% confidence interval
TQ	True	6.7708	0.003	(2.76; 10.78)
Policy	S&P	89.8861	0.000	(85.87; 93.90)
PreTriage	True	0.1286	0.945	(-3.88; 4.14)
HospDist	SpO	6.2156	0.006	(2.20; 10.23)

TQ did not affect arrival times to hospitals significantly, and the evacuation strategy had the most impact on admission delay in the R3 hospitals. Applying TQ reduces the number of deaths and increases the number of people to transport which can have a minor impact on arrival time because more ambulances are requested. The slight increase in MTF mean arrival time in the SpO configuration is caused by the longer distance travelled by the ambulances.

4 DISCUSSION AND LIMITATIONS

The modeled hypothetical scenario presents a depiction of a flawless disaster response, where transports are safe, and the enemy does not disrupt the MCI response. It emphasizes multiple aspects. Firstly, injuries resulting from drone explosions are likely to elicit major hemorrhage unmatched by threats encountered in civilian settings. The target population was unprotected from ballistic explosions and in no specific dug-in position. These situations have been recently reported in the Israel-Gaza war and in the conflict in Ukraine. The number of victims and patients are on par with reports from suicidal drone explosions. The absence of considerations about debris and the 3D space results in a simplified model of blast patterns and injuries but our approach captures the main characteristics of high-explosive detonations.

The modeling of the disaster response is aimed at accelerating the admission of severe patients in local hospitals, and considerations on the time to medical interventions, minimizing mortality outcomes. In this scenario, we assumed equal numbers of EMS resources for each site and nothing in reserve for additional threats. This is a limitation of a more realistic use of an EMS pool but is made to optimize the outcomes. Also, we did not explicitly model a dispatch making such allocations and this will be performed in future research. The treatment model did not distinguish between procedures but provided different outcomes based on location. The focus was placed more on the time delays to admission, with the use of TQ placement, and stabilizing procedures accounted for via a hold of state of health evolutions. Specific doctors, diagnostics, and the use of blood could affect the mortality outcomes on a more granular level but would also complexify the models by a significant margin. We scripted the dispatching of ambulances in this model and varied stochastically the arrival times by an amount of 20% using a truncated normal distribution. For more realism, EMS transports should be considered as agents and communicate with a simulated dispatch to allocate the resources dynamically. There is another major assumption made in the fact that patients reaching the R3 are saved, so only prehospital response is modeled. Further research will consider in-hospital survival outcomes and impact of transport times on mortality. Our current assumptions are overly optimistic, as there is no certainty that surgeries and in-hospital interventions will guarantee patient survival.

5 CONCLUSIONS AND FUTURE RESEARCH

A scenario of three suicidal UAVs in the Brussels city center was simulated using the SIMEDIS simulator. Patient injuries and evolution were determined based on their location respective to the blasts. Analytical probabilistic formulae have been used to determine if patients were hemorrhaging and needed TQ, and if they were incapacitated and needed to be transported to the FMP prior to transport to the hospitals. This research shows that the most key factor determining mortality outcomes is TQ application followed by quick evacuation towards MTFs capable of providing DCS. The fact that TQ results in reduction in mortality has been known for a long time (Kragh et al. 2009; Henry et al. 2021). Stay and Play resulted in higher mortality with victims receiving DCS past their survival windows. The evacuation policy had a direct effect on the admission times to a DCS facility. All evacuations were uncontested and no reserve in transport pool was needed, which may not be the case if additional attacks are expected or if the enemy delivering the threats is active in the area. These considerations imply adding models for a dispatch and a determination of evacuation routes based on local security. The case of an active threat should also be considered to better capture the unknowns associated with surprise attacks.

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