Action: respond to our copy-editing questions

Select each question and describe any changes we should make on the proof. Changes against journal style will not be made and proofs will not be sent back for further editing.

- AQ1. Please check the spelling and accuracy of all author names and affiliations, particularly for any co-authors. Also check that author surnames are correctly highlighted. This is to ensure that forenames and surnames are tagged correctly for online indexing. Incorrect names and affiliations may lead to an author not being credited for their work by funders, institutions, or other third parties. Make any changes directly in the text. Note that changes to your authorship list (adding or removing authors, changing designation of corresponding author) require additional approvals. Email jnls.author.support@oup.com if this is required.
- AQ2. If your manuscript has figures or text from other sources, please ensure you have permission from the copyright holder. Also ensure that the copyright owner is properly credited, for instance in the figure legends. Make any changes directly in the text. For any questions about permissions, contact jnls.author.support@oup.com.
- AQ3. Please check that funding is recorded in a separate funding section, if applicable. Use the full official names of any funding bodies and include any grant numbers. Insert any changes to the funding section directly in the text.
- AQ4. Please ensure all “conflicts of interest” (or “disclosures”) have been included for you and your co-authors, and that this section is correct. Edit the text directly if changes are required.
- AQ5. Please provide city and department for affiliation 3 directly in the text.
- AQ6. Please provide department for affiliation 4 directly in the text.
- AQ7. Please provide postal code for affiliation 6 directly in the text.
- AQ8. Please provide postal code for affiliation 7 directly in the text.
- AQ9. Please provide the Issue for reference [3] directly in the reference.
- AQ10. Please provide the page range for reference [11] directly in the reference.
- AQ11. Please provide the journal title for reference [14] directly in the reference.
- AQ12. Please provide the page range for reference [16] directly in the reference.
- AQ13. Please provide the issue and page range for reference [18] directly in the reference.
- AQ14. The caption for Figure 2 currently contains reference to colour used within the figure. For accessibility purposes reference to colour should be avoided. If possible, please update the wording for the figure caption to remove reference to colour.

Action: check your manuscript information

Please check that the information in the table is correct. We use this information in the online version of your article and for sharing with third party indexing sites, where applicable.

Full affiliations Each unique affiliation should be listed separately; affiliations must contain only the applicable department, institution, city, territory, and country.	1Department of Mathematics, Royal Military Academy Brussels, B-1000, Brussels, Belgium 2Medical Service Capability and Force Development, Bundeswehr Medical Academy, Munich, 80937, Germany 3Unconventional Solutions, Inc, Box Elder, SD 57719, United States) 4NATO Centre of Excellence for Military Medicine, Interoperability Branch, Budapest, H-1555, Hungary) 5East Surrey Emergency Department, Canada Avenue, Redhill, RH5-5RH, United Kingdom 6Prague Center for Global Health, Charles University, Prague, Czech Republic) 7Department of the Army, 4th Security Force Assistance Brigade, Fort Carson, CO, United States)
Group contributors The name of the group and individuals in this group should be given, if applicable (e.g. The BFG Working Group: Simon Mason, Jane Bloggs)	NA
Supplementary data files cited	NA
Funder Name(s) Please give the full name of the main funding body/agency. This should be the full name of the funding body without abbreviation or translation, if unsure, see https://search.crossref.org/funding	

MILITARY MEDICINE, 00, 0/0:1, 2025

Recreating the Vigorous Warrior and Clean Care Exercises *In Silico*: A Proof-of-Concept Study for the Digital Transformation of Military Medical Support

Mehdi Benhassine, PhD[1]; Lt (OF-1 GER) Kai Meisner, MSc[2]; Maj (OF-3 USAF) David Stewart, MBA, PA-C, TP-C, (Ret.)[3]; Col (OF-5 ROU) Daniel Ianc, MD[4]; Col (OF-5 SVK) Marián Ivan, MD, MPH[4]; John Quinn, MD, MPH, PhD[5,6]; Maj (OF-3 USA) Travis Kaufman, DMSc, APA-C[7]; LtCol (OF-4 BEL) Filip Van Utterbeeck, PhD Eng[1]

ABSTRACT

Introduction:

Computer simulations are becoming increasingly important in addressing the inherent limitations of medical planning for large-scale combat operations (LSCO). This technology offers a unique capability to model complex tactical scenarios that have not been encountered in past operations. The purpose of this study is to examine the use of computer simulations in enhancing military medical support for LSCO.

Methods:

We collected and analyzed data from the NATO Live Exercise (LIVEX) Vigorous Warrior/Clean Care (VW/CC'24), incorporating both quantitative and qualitative observations from the point of injury to various levels of care, including Role 1, Role 2, and Role 2E. Our assessment focused on triage, damage control resuscitation, damage control surgery, and decontamination. The data was employed to recreate the scenario with a discrete-event computer simulator named SIMEDIS. The simulation was developed based on hourly observations recorded by the research team. The placement and capacities of Military Medical Treatment Facilities within the exercise were integrated into the model. Each simulated casualty was assigned injuries and clinical progressions as defined in the LIVEX scenario. Laydown of Military Medical Treatment Facilities within the exercise, along with their capacities, were incorporated.

Results:

Transport, triage, and treatment processes were simulated using procedural guidelines and time estimates derived from observations made during VW/CC'24. The simulation of the LIVEX within SIMEDIS is presented, and the number of ambulances is varied with a direct impact on mortality.

Discussion:

This report focuses on the similarities between the LIVEX and the computer simulation although also identifying gaps relevant to LSCO scenarios. The application of modeling and simulation to a LIVEX aims to establish a precedent for its use in future events beyond traditional table-top exercises, offering a novel methodology based on real field measurements. The objective is to utilize computer simulations to estimate clinical timelines and create a test platform for assessing and evaluating LSCO scenarios in a cost-effective way in a safe-to-fail environment. This approach enhances LIVEX planning by enabling the simulation of large-scale casualty influxes and logistical challenges without the need for extensive personnel mobilization.

[1]Department of Mathematics, Royal Military Academy Brussels, B-1000, Brussels, Belgium

[2]Medical Service Capability and Force Development, Bundeswehr Medical Academy, Munich, 80937, Germany

AQ5 [3]Unconventional Solutions, Inc, Box Elder, SD 57719, United States)

[4]NATO Centre of Excellence for Military Medicine, Interoperability Branch, Budapest, H-1555, Hungary)

AQ6 [5]East Surrey Emergency Department, Canada Avenue, Redhill, RH5-5RH, United Kingdom

[6]Prague Center for Global Health, Charles University, Prague, Czech Republic)

AQ7 [7]Department of the Army, 4th Security Force Assistance Brigade, Fort Carson, CO, United States)

AQ8 The views expressed in this material are those of the authors, and do not reflect the official policy or position of the U.S. Government, the DoD, or the Department of the Army.

Presented as an oral presentation at the 2024 Military Health System Research Symposium, Kissimmee, Florida; MHSRS-24-11,614.

Corresponding author: Mehdi Benhassine (mehdi.benhassine@mil.be).

doi:https://doi.org/10.1093/milmed/usaf178

Conclusion

: The integration of computer simulations with military exercises offers a powerful method for improving LIVEX preparation to meet training objectives and can also be tailored for medical planning in LSCO. By leveraging data-driven modeling, military planners can better predict, assess, and optimize medical responses and courses of actions, ultimately enhancing readiness for LSCO.

INTRODUCTION

A New Medical Support Paradigm

Over the past two decades, NATO's medical Concepts of Operations (CONOPS) have centered on counterinsurgency, relying on air superiority, sufficient medical resources, and low casualty rates to ensure timely treatment of wounded personnel. However, Russia's hybrid warfare against Ukraine since 2014, culminating in its full-scale invasion in 2022, has heightened geopolitical tensions and poses significant challenges to NATO's defense structures and allied support systems. These developments underscore the need to adapt NATO's strategic concept. [1] Accordingly, CONOPS must be revised based on evidence-driven principles. Anecdotal reports from the Ukraine war indicate casualty numbers far exceeding those in NATO's Afghanistan operations, suggesting that future large-scale conflicts could involve a sharp rise in both patient volume and injury severity. [2–4] Rapid medical treatment remains crucial to reduce morbidity and mortality. Meanwhile, targeted attacks on healthcare facilities have compelled Ukrainian leaders to develop alternative care structures.[4,5]

Underground hospitals and mobile care units, coordinated by entities such as the International Committee of the Red Cross, have sustained critical healthcare services in Ukraine.[6] Collaborative efforts between the WHO, Médecins Sans Frontières, and local healthcare providers have enabled the distribution of medical supplies and training healthcare workers.[7] Strengthening these partnerships not only ensures the immediate continuation of care but also builds long-term capacity and resilience in war-affected areas, enabling health systems to better respond to the challenges posed by contemporary warfare.

NATO Standardization Agreement 2228, outlined in the Allied Joint Medical Support Doctrine (AJP-4.10),[8] provides the framework for joint medical support in NATO operations, integrating civilian and military entities. Medical Treatment Facilities (MTFs) are categorized by NATO roles (Role 1 (R1), Role 2 Basic (R2B), Role 2 Forward (R2F), Role 2 Enhanced (R2E), Role 3 (R3), and Role 4 (R4)), with each role offering progressively advanced capabilities, positioned further from the front line. Although the conventional approach follows this order, tactical situations and resource limitations may require skipping roles. Additionally, medical personnel fatigue and the need for R1 or R2 redeployment because of infrastructure damage must be considered in large-scale combat operations (LSCO).

Strategies to Improve Medical Readiness

To support best practices in medical planning, new strategies for evacuating patients in dynamic contexts require methodological approaches through "wargames" or "table-top exercises" (TTXs), where participants role-play various scenarios and contingencies in a controlled environment. A higher-fidelity and more practical approach involves Live Exercises (LIVEXs), where events and casualties are re-enacted by role-players. This method allows for the simulation of threats with varying levels of authenticity, enabling responders to practice elements of direct patient care, transportation, and perform medical procedures in a controlled yet dynamic environment accounting for variables.

The Modeling and Simulation Approach

Modeling and Simulation (M&S) offers an alternative approach, running multiple statistically independent scenarios without direct human intervention. Subject Matter Experts (SMEs) or analysts define the parameters, enabling the evaluation of various scenarios and statistical analysis of key impact factors. This method, known as Constructive Simulation, differs from Live or Virtual simulations, which focus on training rather than planning and decision-making.[9] Despite its potential, M&S has yet to be widely integrated into military operations because of cultural barriers. We aim to demonstrate its benefits for both LIVEX and operational planning.

Simulation models vary in granularity, with higher detail requiring more real-world data. However, data limitations often necessitate assumptions from SMEs. As complexity increases, these models may function as opaque systems, wherein outcomes arise from intricate interactions that are not immediately transparent. Rigorous validation is crucial to establish trust and ensure acceptance. To enhance this, we incorporate observations and firsthand data from the NATO 2024 Vigorous Warrior and Clean Care LIVEX (VW/CC'24) experiment described[10] into a closed-loop simulation system, improving validation and SME engagement. Organized by the NATO Centre of Excellence for Military Medicine (MILMEDCOE), VW/CC'24 is the Alliance's largest military medical interoperability exercise. The LIVEX is designed in the frame of a NATO Article 5 collective defense against a near-peer adversary in training the Alliance to treat and care for large casualty influx.

Another advantage of leveraging M&S is its cost-effectiveness especially when working at scale. Methods of Live and Virtual M&S often require extensive computer resources to model large number of casualties in a realistic 3D environment with little benefit for planning resource allocations. Training is to be seen as a separate objective and humans must be solicited to "run" the simulations.

This research explores the benefits of integrating field measurements and observations with scenario replay to validate software predictions and leverage algorithms for alternative outcomes. In LSCO, historical cases based on modern medical support doctrine lack empirical support. To address this, the VW/CC'24 exercise was recreated in the SIMEDIS (simulation for the assessment and optimization of medical disaster management) simulator, replicating real locations and patient flow. Injuries and their progression were simulated, with timelines derived from field measurements and scripted injects. The following analysis compares the simulator's predictions with observed outcomes during the live exercise, reporting on field data, the scenario, and a 1-day recreation of the LIVEX using SIMEDIS.

METHODS

This section outlines the adaptation of the SIMEDIS simulator model, and the scenario used in VW/CC'24. SIMEDIS operates by simulating casualty streams over time through a sequence of discrete events. Each event—such as the arrival of a new casualty, a triage process, or a medical treatment—alters the system's state. The actual time duration of these events, sampled out of a time distribution, serves as a critical input parameter for the simulations. Unlike continuous simulation methods, this discrete-event approach enables the efficient modeling of large systems and long-term scenarios without compromising performance.

SIMEDIS Simulator

The SIMEDIS simulator is a stochastic discrete-event simulator that recreates the prehospital medical response in the aftermath of a myriad of threats ranging from conventional to chemical, biological, radiological, nuclear, and explosive/environmental/endemic (CBRNE) weapon systems. Originally tailored at civilian response,[11–13] it was adapted first to war-related threats,[14] and includes concepts from NATO medical support doctrine.[8] Each event, or threat, generates casualties on the map. Every casualty's location and clinical status are saved to the output database, and a medical response is simulated. The health state of each casualty is modeled via a continuous mathematical model whose parameters depend on the casualty's Injury Severity Score (ISS) or Military Combat Injury Score (MCIS)[15] and the age, along with intoxication levels for CBRNE. The setting of the ISS or MCIS is based on military medical clinicians and planners SMEs' opinion and the description of the injuries in each standardized casualty card (or patient card). A link is established between ISS/MCIS and the estimated time of death if no medical procedure or lifesaving intervention is provided to the casualty.[10,16] To account for medical procedures' effects on casualty clinical status, a set of improvement equations is used and parameterized by SMEs. For CBRNE-related injuries, we use the injury profiles defined in the NATO Standards Related Document for the AMed-P7.5-1 for Sarin (GB) as further researched by the authors for use in the simulator.[17,18] Input parameters include the number of ambulances, the number of medical supplies, and the capacity as well as capabilities of each MTF. Medical procedures are also modeled, including triage and triage reassessment, damage control resuscitation (DCR) and damage control surgery (DCS), the application of tourniquets (TQ), antidote application for nerve agents, following established Clinical Practice Guidelines.[19,20] Triage is modeled upon first contact with a responder. Depending on whether the casualty is ambulatory or not, he/she is loaded on an available litter and transported towards the closest established Casualty Collection Point (CCP). In NATO terminology and doctrine, triage categories are T1 (Immediate), T2 (Urgent), T3 (Delayed/routine), and T4 (Expectant).

Simulated Casualties are spawned at the point of injury/point of exposure (PoI/PoE) and are transported to a CCP. Once at the CCP, triage occurs and transport to a R1 is simulated. From the R1, DCR is simulated and subsequent transports to a R2 follows where triage occurs again before DCS ensues. There is also the possibility of transporting a casualty straight from the CCP to a R2, or from a R2 to another R2 to optimize medical resource utilization. In the simulator output, map tiles are used to visualize casualties, responders, and MTF laydown. The disaster response is scripted by a series of instructions and policies which vary between simulation runs.

During VW/CC'24, the location of all casualties was known to the ambulance drivers via the presence of a NATO Patient Evacuation Coordination Cell (PECC). The MTF laydown and CCP locations, known from the LIVEX plan, were also recreated in the simulation. This information facilitated the recreation of the LIVEX scenario within SIMEDIS. Once the casualty was created in the simulation and geolocated with a set of injuries and health state value, an algorithm determined the first life-saving interventions that the casualty needed based on available supplies from the soldier's kit; a "combopen" constituted of atropine and pralidoxime if the casualty was exposed to a chemical agent, and/or a TQ if the casualty had peripheral hemorrhage. The casualty applied these specific lifesaving interventions if able in the form of "self-aid," or a nearby combatant/rescuer performed the interventions as "buddy aid." The locations of CCPs were prescribed and defined at VW/CC'24. Therefore, there was no modeling to account for finding a safe location to transport casualties to as a CCP or stabilization point. Transport priority was based on triage and personnel availability. In the case of a mass casualty incident ("MASCAL"), T1 patients were given priority followed by T2 for medical evacuations (MEDEVAC). The simulator accounted for travel and transport times (which include loading and/or unloading a patient to the ambulance or vehicle of opportunity). Transport destination was determined by an algorithm which establishes,

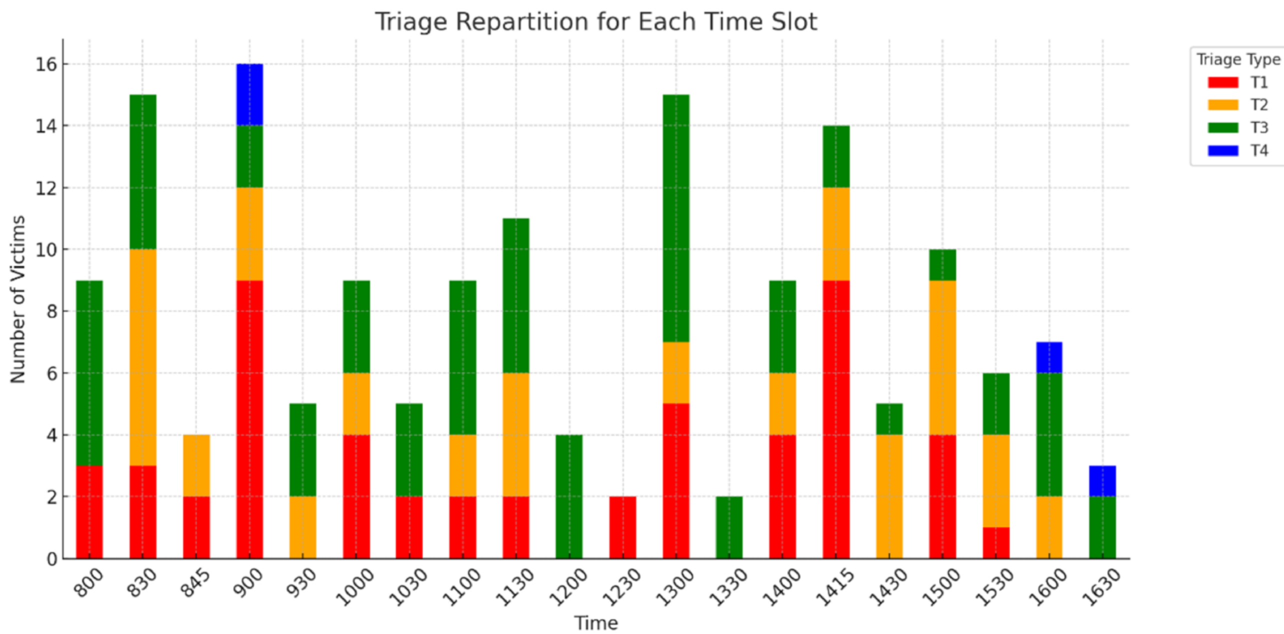


Figure 1. Schedule (noted in time format hhmm) and triage repartitions for injects of Day 1 for Brigade 1 (BDE 1).

from the known MTF network, the closest hospital to the CCP which can admit the patient and has capacity. By design, the closest MTF to a CCP were R1 MTFs, but some patients were scripted in the scenario to walk in at a R2 facility. In this case, the casualty went to triage, stabilization with DCR, and DCS when clinically indicated, or transport to a higher echelon of care. For R1 and R2, the holding time of casualties were limited especially in MASCAL situations, especially for those patients post DCR/DCS requiring Intensive Care Unit (ICU) support. We ensured that these times aligned with observations in the field.

VW/CC'24 Scenario and Input MTF Laydown

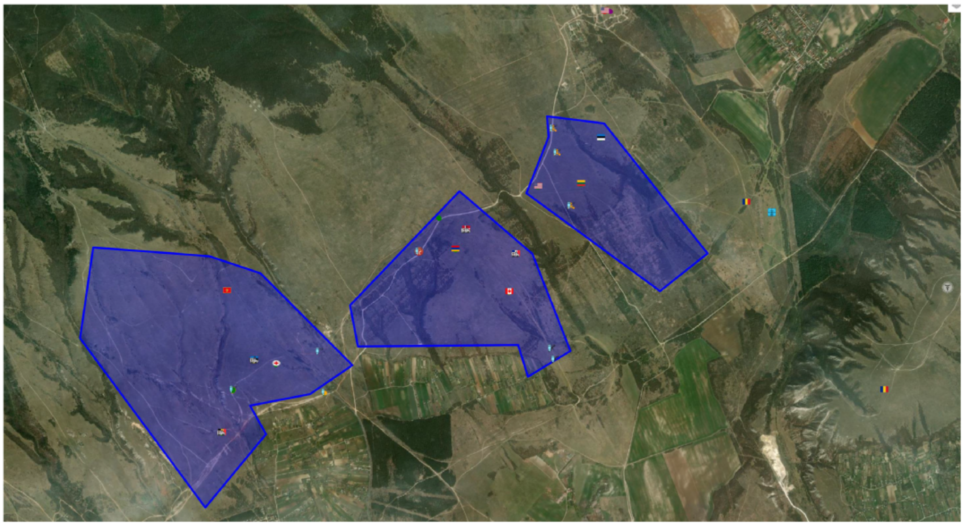
The simulated crisis scenario was based on NATO's OCCASUS Exercise model within a fictional environment. Predefined operational phases justified the influx of casualties. Day 1 (D1) represented a 7-day Delay Operation aimed at hindering enemy advancement. Days 2 and 3 (D2–D3), simulated to occur 7 days after D1, corresponded to Defensive Operations designed to establish conditions for (counter-)offensive actions. Day 4 (D4), occurring 14 simulated days after D3, represented a counter-offensive operation to secure the border. Finally, Day 5 (D5), simulated 6 days after D4, represented a Stabilization Operation. The input database was composed of the complete list of MTFs at VW/CC'24. The database specified the role of each MTF and whether it was equipped to provide DCR, DCS, and/or able to perform casualty decontamination. Additionally, the database included the geographical coordinates and hourly capacity of each facility. Furthermore, information on all ambulances and evacuation vehicles, including their initial coordinates, was incorporated into the dataset.

VW/CC'24 Casualty Injects

Each day, an average number of 275 casualties were simulated by role-players in the following average triage repartitions per day: 35.96% T1, 29.43% T2, 30.82% T3, and 3.79% T4 casualties per day.

Casualties presented a mix of trauma, burns, CBRNE, and CBRNE with traumatic injuries resulting from an array of events including conventional and chemical artillery explosions, Troops in Contact, Improvised Explosive Devices, Radiological Dispersal Devices, building fires, and an unknown disease. The initial location of casualties was dependent on each inject, some of them appearing at a designated CCP or directly at a R1 or R2, in which case we defined the start location of a patient at the R2 coordinates. Each T1 role-player was assigned a case manager managing the patient's evolution. Each day, the total planned casualties were scheduled in the 0800 to 1600 timeframe by 30-minute intervals. Most of the time, events were scripted to generate multiple casualties simultaneously, simulating MASCALs. The total number of patients was distributed across two brigades (Brigade 1 (BDE 1) and Brigade 2 (BDE 2)). Figure 1 presents the schedule along with triage breakups for Day 1 of the LIVEX for BDE 1.

For simplicity and to compare with observations during the LIVEX, we recreated the same injects, totaling 167 victims. The possibility of recreating the schedule of patients in the simulator presents advantages. First, variations in the schedule allow to experiment more MASCALs throughout the day at no cost, and artificially stress-test the MTFs. The triage mix and injuries can be modified at will, by insisting more on CBRNE or trauma victims, highlighting key differences in requirements both in terms of MTF type and medical coun-



AQ14 **Figure 2.** BDE 1 layout as part of the SIMEDIS simulator visualization output. In blue, the three multinational Battalions' MTFs constituting BDE 1.

termeasures and logistics. Our approach remains exploratory and showcasing the possibilities of employing M&S, but additional quantitative analysis and experimentation is possible.

RESULTS

The schedule of planned casualties for Day 1 of the LIVEX for BDE 1 was scripted, comprising three Battalions (Bn). We located each casualty using latitude and longitude coordinates and time throughout the simulation. A visual representation of the BDE 1 MTF laydown as well as limits for areas of responsibility are depicted in Figure 2.

Building on the inject definition, health state evolution parameters were determined using the estimated MCIS score and known injury types, including trauma (amputations, penetrating injuries), blast and fragmentation injuries, chemical injuries, and radiological injuries.

Collected Casualty Clinical Timelines Data from the Field

As described in our precedent article,[10] we conducted an experiment during the LIVEX, focused at collecting timeline for selected patients, to obtain baseline values for triage, DCR, DCS, and decontamination times. We focused the collection of patient clinical timelines on selected MTFs, because of the limited number of experimenters and the number of simultaneous casualties to track. The collected field data are displayed in **Table 1**.

Table 1. The Input Parameters and Timing Reference Values (as Measured in the Experiments) are Reported in Table 2 for Collected Field Data With Selected T1 CBRN and Trauma Victims Versus Trauma Only Selected T1 Victims.

Metric (mins)	T1 CBRN + trauma	T1 trauma
Triage time	1.38 ± 0.65	2.3 ± 0.1
Stretcher load time	1.44 ± 0.25	1.12
DCR time	18.4 ± 8.4	26.5
DCS time	N/A	54 ± 1
Disrobe time	3.5 ± 0.6	N/A
Agent ID time	4.2 ± 2.1	N/A
Decon time (immobile)	15.5 ± 5.3	N/A
Decon time (mobile)	8.0 ± 5.3	N/A

Parameter Space in the Computer Simulations

Between simulations runs, we varied the following parameters:

- The number of ambulances available. In the VW/CC'24 planning, a set number of ambulances were assigned to all MTFs. We used a varying number of ambulances in simulation runs from 2 up to 30 ambulances for BDE 1 only.
- The patient distribution policy, as transport destinations were not unique, i.e., different MTFs could receive a patient at a given time. We set a criterion, used in previous scenarios, of either transporting the patient to the Closest MTF available (with a parameter named "CloseFirst") versus a random distribution amongst the available MTFs (with a parameter named "SpreadOut").

Each simulation run, with its unique set of input parameter values, was replicated 30 times to account for changes in time points.

Impact of Ambulance Numbers on Mortality

During VW/CC'24, each MTF was allocated one civilian ambulance from the Romanian Department for Emergency Situations (DSU). In addition, armored ambulances from Denmark and military ambulances from Belgium and Luxembourg were utilized. Given the MTF laydown presented in

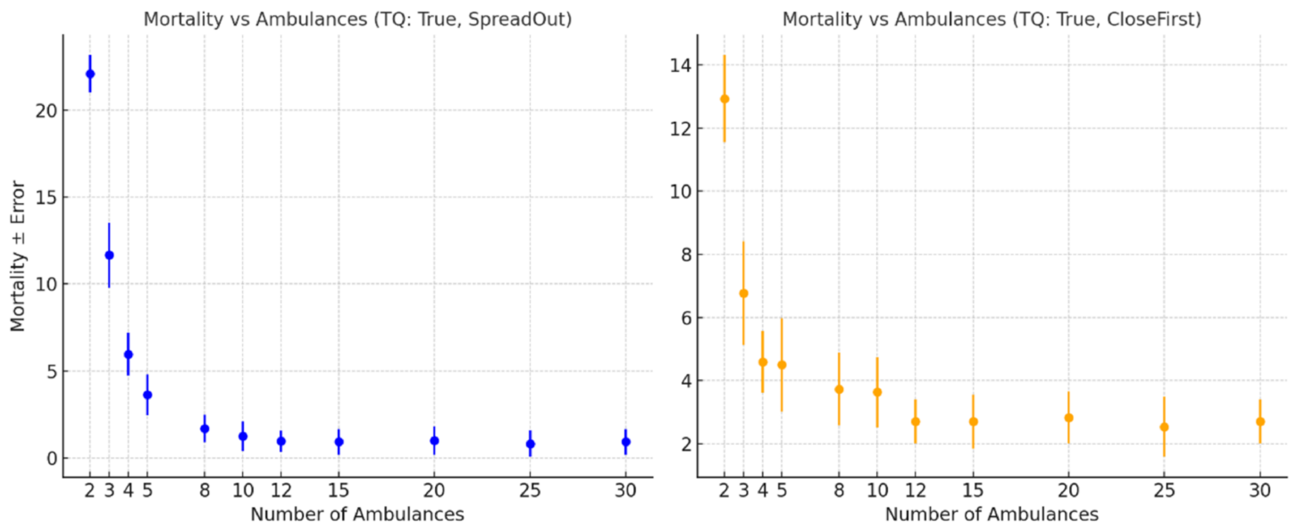


Figure 3. Impact of the number of ambulances on mortality for two distribution policies: SpreadOut (random MTF) and CloseFirst (closest available MTF).

Figure 2, the base allocation for civilian ambulances in BDE 1 consisted of nine ambulances, supplemented by some of the sixteen reserve ambulances, which were dispatched via the PECC and available to both brigades. In the VW/CC'24 scenario, this number was deemed sufficient to handle the daily injects, ensuring that all casualties survived unless specifically scripted to die within the scenario. Figure 3 shows the variation in mortality outcomes versus the number of available ambulances to transport all victims for BDE 1. The difference between the two plots is the MTF distribution policy for patients. The simulator indicates that lower mortality outcomes result from transporting patients to the closest available MTF ("CloseFirst" parameter) rather than dispersing them to minimize MTF saturation (with the "SpreadOut" parameter).

In both cases, nine ambulances were a threshold in this scenario above which mortality outcomes did not vary much and were close to what was available during the LIVEX. But as the simulation results indicate, reducing the number of ambulances further results in an increase in mortality outcomes (up to a 4-fold increase). During the LIVEX execution, we observed issues with ambulances not arriving at the right destination and drivers getting lost. We believe that a simulation model as we have built could help in rehearsing ideal cases before execution to mitigate some of these planning issues. Another notion of ambulances being part of a pool of transports rather than belonging to a specific MTF or Nation simplified the outcomes but affected the LIVEX which we define in this article as "communication issues."

DISCUSSION

Employment of M&S for the purpose of creating a replay of the VW/CC'24 exercise addresses gaps and provides a novel methodology. The transformative potential of M&S in advancing medical planning and response capabilities in LSCO for NATO and NATO partners are described. Integrating the SIMEDIS simulator with insights gained from VW/CC'24 offers a novel approach to addressing the complexities of modern battlefield medicine. The comparative analysis of M&S and LIVEX reveals both their unique strengths and limitations, providing a roadmap for enhancing preparedness in future conflict scenarios. M&S stands out for their ability to evaluate a wide array of scenarios and contingencies rapidly and cost-effectively. Unlike LIVEX, where constraints such as time, resources, and participant fatigue restrict the scope and repeatability of scenarios, simulations enable sensitivity analyses that reveal critical bottlenecks in medical response systems; and can be applied in several iterations with minimal risk. For instance, this study demonstrated how ambulance/vehicle availability significantly impacts mortality rates, insights that would be challenging to derive from a single iteration of a live exercise. Additionally, simulations allow for controlled experimentation with input parameters, offering a statistically rigorous evaluation of various operational strategies.

LIVEX incorporates human factors—such as decision-making under stress, moral dilemmas, and operational friction—that add a level of realism often absent in M&S. Especially when different nations train and fight together, interoperability and language barriers significantly impact effectiveness. For example, VW/CC'24 revealed critical aspects of interoperability between civilian and military actors, emphasizing the need for seamless coordination across sectors in complex disaster or combat scenarios.

This experimental study underscores the value of leveraging both approaches in tandem. Modeling and simulation can complement TTX and LIVEX by providing a scalable and iterative platform for testing strategic and tactical decisions. Table-top exercise refines high-level strategies, although LIVEX offers the realism of operational conditions, including the unpredictability of human responses. Together, these methods create a comprehensive framework for military medical training and doctrine development; most notably for NATO in the presence and preparation of LSCO. Despite these advancements, the study identifies key areas for improvement. Applications of this simulation model include modifications in the MTF laydown and capacities, studying the impact of shortage of supplies on mortality outcomes, changing the number or schedule of victims navigating through separate phases of operations, and the impact of R2F relocation in the simulation scenario, if the tactical situation requires it. AI can be leveraged to generate victims based on historical patient data from trauma registries with treatment outcomes determined from clinical data. Another improvement consists in introducing persistent threats and denial in the evacuations in the form of drone agents in the simulation. Current simulations lack dynamic battlefield conditions, such as targeted attacks on medical personnel, personnel fatigue and stress, and facilities or equipment failures, which are critical in real-world LSCO.

We believe that using a hybrid approach where visualization has an important aspect, rendering part of the analysis more accessible to an array of experts who are not necessarily used to interpreting data-driven analysis, is a key enabler for acceptation of M&S in real-world settings, including military operations, where quick decisions must be made in the field. M&S, thanks to its safe-to-fail environment can test alternative Courses Of Actions (COAs) at no materiel and personnel cost, in order to save lives before engaging in dangerous situations.

Limitations

The reliance on assumptions and predefined parameters within simulations introduces limitations. Although SMEs play a crucial role in shaping these inputs, the outcomes may lack validity in highly dynamic and unpredictable LSCO environments. This study has several limitations that should be addressed in future research. In the presented simulations, we did not consider that the personnel in charge of the rescue were targeted, and we also did not consider failing equipment, and damages to MTFs but these remain crucial events to consider in future models. The simulations relied heavily on assumptions and predefined parameters set by SMEs, which may not fully capture the dynamic and unpredictable nature of LSCO. Additionally, critical real-world variables, such as targeted attacks on medical personnel, equipment failures, access to adequate blood supplies and adversarial tactics, were excluded from the simulations.

CONCLUSIONS

The evolving nature of modern warfare necessitates a change in thinking in NATO's medical support strategies. The lessons learned from Ukraine conflict highlight the need for adaptable and resilient medical logistics, emphasizing real-time casualty management, alternative care structures, and robust collaboration between military and civilian healthcare entities. The use of simulation-based planning tools, such as SIMEDIS, provides critical insights into casualty flow dynamics, resource allocation, and the impact of logistical constraints on patient outcomes. Our analysis of the VW/CC'24 exercise demonstrates the value of modeling and simulation in refining casualty evacuation protocols and optimizing resource distribution. The findings indicate that ambulance availability, transport prioritization, and MTF selection significantly influence survival rates, reinforcing the need for data-driven decision-making. Furthermore, integrating field observations into simulation models enhances validation, improving operational preparedness for large-scale combat scenarios. Moving forward, NATO must prioritize the incorporation of evidence-based casualty estimation models, real-time simulation exercises, and improved interoperability among allied medical units. By leveraging these approaches, NATO can enhance its medical readiness and ensure a more effective response to the complex challenges of contemporary warfare.

ACKNOWLEDGMENTS

The authors would like to thank the MILMEDCOE for letting the authors participate in the VW/CC'24 LIVEX to perform the data collection experiment as part of the Concept Development and Experimentation part of the LIVEX.

FUNDING

This study was funded by the Royal Higher Institute for Defense with grant HFM/21-12.

CONFLICT OF INTEREST STATEMENT

None declared.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author. All data is freely accessible, open-source and nonsensitive.

INSTITUTIONAL REVIEW BOARD (HUMAN SUBJECTS)

Not applicable.

INSTITUTIONAL CLEARANCE

Institutional clearance approved.

REFERENCES

1. NATO - Topic: Strategic Concepts. Accessed October 2, 2024. https://www.nato.int/cps/en/natohq/topics_56626.htm
2. Russia and Ukraine Each Have Over 100,000 Casualties, Top US General Says - The New York Times. Accessed October 2, 2024. https://www.nytimes.com/2022/11/10/world/europe/ukraine-russia-war-casualties-deaths.html
3. Remondelli MH, Remick KN, Shackelford SA, et al. Casualty care implications of large-scale combat operations. *J Trauma Acute Care Surg*. 2023;95:S180–4. 10.1097/TA.0000000000004063 AQ9
4. Remondelli MH, McDonough MM, Remick KN, et al. Refocusing the Military Health System to support Role 4 definitive care in future large-scale combat operations. *J Trauma Acute Care Surg*. 2024;97(2):S145–53. 10.1097/TA.0000000000004379

5. Hell, horror and heroism in Ukraine's battlefield hospitals. Accessed January 15, 2025. https://www.economist.com/europe/2024/11/03/hell-horror-and-heroism-in-ukraines-battlefield-hospitals?giftId=e91f3b1e-8220-44dc-98c0-3d179fdcbc27&utm_campaign=gifted_article
6. Russia-Ukraine international armed conflict: one year of the global Red Cross Red Crescent Movement response | IFRC Accessed December 2, 2024. https://www.ifrc.org/document/russia-ukraine-international-armed-conflict-one-year-global-red-cross-red-crescent
7. 1000 days of war in Ukraine: resilience in health response, recovery and reform efforts despite attacks and ongoing challenges Accessed December 2, 2024. https://www.who.int/europe/news-room/18-11-2024-1000-days-of-war-in-ukraine—resilience-in-health-response—recovery-and-reform-efforts-despite-attacks-and-ongoing-challenges
8. NATO STANDARDIZATION OFFICE (NSO) NATO Standard AJP-4.10 JOINT DOCTRINE FOR MEDICAL SUPPORT Edition C Version 1. 2019.
9. Turnitsa C, Blais C, Tolk A. *Simulation and Wargaming*. John Wiley & Sons; 2021:1–415.
10. Benhassine M, Quinn J, Stewart D, et al. Advancing Military Medical planning in large scale combat operations: insights from computer simulation and experimentation in NATO's Vigorous Warrior Exercise 2024. *Mil Med*. 2024;189(Supplement_3):456–64. 10.1093/MILMED/USAE152
11. Debacker M, Van Utterbeeck F, Ullrich C, Dhondt E, Hubloue I. SIMEDIS: a discrete-event simulation model for testing responses to mass casualty incidents. *J Med Syst*. 2016;40(12). 10.1007/s10916-016-0633-z AQ10
12. De Rouck R, Benhassine M, Debacker M, Utterbeeck Van F, Dhondt E. Optimizing Medical Care during a Nerve Agent Mass Casualty Incident using Computer Simulation. Published online December 13, 2023. 10.21203/RS.3.RS-3735477/V1
13. De Rouck R, Debacker M, Hubloue I, et al. *SIMEDIS 2.0 : ON THE ROAD TOWARD A COMPREHENSIVE MASS CASUALTY INCIDENT MEDICAL MANAGEMENT SIMULATOR*
14. Benhassine M, Van Utterbeeck F, De Rouck R, et al. Open-air artillery strike in a rural area: a hypothetical scenario. 2024:2391–402. 10.1109/WSC60868.2023.10407285 AQ11
15. Champion HR, Holcomb JB, Lawnick MM, et al. Improved characterization of combat injury. *J Trauma - Injury Infect Crit Care*. 2010;68(5):1139–50. 10.1097/TA.0b013e3181d86a0d
16. Benhassine M, De Rouck R, Debacker M, et al. Simulating victim health state evaluation from physical and chemical injuries in mass casualty incidents. *New Trends Comput Sci*. 2023;1(2). AQ12
17. *STANDARDS RELATED DOCUMENT SRD AMedP-7.5-1 Technical Reference Manual NATO Planning Guide for the Estimation of CBRN Casualties Edition A Version 1*. 2018.
18. De Rouck R, Benhassine M, Debacker M, et al. Creating realistic nerve agent victim profiles for computer simulation of medical CBRN disaster response. *Front Public Health*. 2023;11. 10.3389/fpubh.2023.1167706 AQ13
19. Barbee G, Defeo D, Gonzalez C, et al. *Chemical, Biological, Radiological and Nuclear (CBRN) Injury Part I: Initial Response to CBRN Agents (CPG ID: 69)*. 2018.
20. Washburn G, Powell P C D, Callaway DW, et al. JOINT TRAUMA SYSTEM CLINICAL PRACTICE GUIDELINE (JTS CPG) Damage Control Resuscitation (DCR) in Prolonged Field Care (PFC) Published online 2018.