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OPTIMIZING MILITARY LOGISTICS: A SIMULATION-BASED APPROACH

Summary. This paper examines the influence of transport distance on the performance of casualty evacuation and supply replenishment systems using a simulation-based approach. 0Simulations conducted in the MasaSword program focused on a mechanized battalion operating within brigade to verify two hypotheses: (1) that reducing the distance between first-line units and the medical base from 100 km to 50 km will expedite the evacuation process and (2) that reducing the distance between first-line units and the logistics base from 100 km to 50 km will improve the replenishment of food and water supplies. The study quantified evacuation completion times, the proportion of non-evacuated casualties, and supply depletion rates under varying transport distances and operational conditions. Sensitivity analyses considering vehicle availability and weather effects were also performed. The results show that increasing transport distance significantly degrades system performance, leading to evacuation capacity shortages and accelerated supply depletion. A reduction in distance from 100 km to 50 km resulted in the complete evacuation of wounded personnel and improved supply sustainability. The present study highlights the importance of optimizing the placement of logistics and medical bases to enhance operational efficiency. It also underscores the value of simulations as a decision-making tool for military logistics planning. Properly positioned support infrastructure can reduce risk, improve resource allocation, and increase mission success rates. The proposed simulation framework provides a transferable methodology applicable not only to military logistics but also to emergency transport and remote-area supply systems requiring robust planning in situations involving uncertainties.

1. INTRODUCTION

Military logistics relies on host nation support, coalition contributions, and national stockpiling. Inventory management uses consumption standards and predictive modeling of demand [1, 2].

Current procedures often overlook operational risks and uncertainties. Decisions regarding base locations, resupply timelines, and evacuation protocols are not fully standardized. This study addresses these gaps using simulation-based analysis, allowing for dynamic evaluation and risk-informed decision-making [3, 4]. Modeling and simulation are appropriate apparatuses for evaluating variants of air enemies' activities, and based on such results, it is possible to choose the optimum battle configuration of one's own forces [3]. The formulation of hypotheses and the implementation of specific experiments are the research methodologies used [4].

Recent literature emphasizes agent-based simulations, Vehicle Routing Problem (VRP) optimization, and stochastic modeling as tools for evaluating combat logistics [5–9]. This work

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complements these approaches with a practical field-oriented case study and is part of the study on the issue of logistics education, which addresses strengths, weaknesses, risks, and opportunities for quality content [10].

2. DESCRIPTION OF THE PROBLEM AND METHODOLOGY

Several methods, theories, and approaches can be used to manage supply chain activities. Inventory management theory, risk management, and optimization of supply routes [11, 12] can be used to manage activities in a supply chain. The following approaches are applied:

- Inventory management theory: Determines min/max stock levels and replenishment cycles (Q- and P-systems).
- Risk management: Evaluates operational uncertainties, including vehicle losses, weather effects, and supply chain disruption [13].
- Route optimization: VRP and TSP models are applied to minimize travel distance and time [14, 15].

2.1. Management of Supply Chain Activities

Inventory management theory is used to determine the basic characteristics of the selected inventory management system. Risk management [8] identifies and evaluates risks that may affect the supply chain. Methods associated with the optimization of supply routes are used to determine the shortest distances with regard to the order of delivery or collection of supplies.

There are two basic inventory management systems [2]:

- Q system: A signal status of stocks is determined, and the same amount of stock is constantly replenished. The interval to repeat the order is variable.
- P system: The execution of the order is carried out in the same time intervals with different quantities. The size of the order is determined as the difference between the maximum quantity, the so-called upper order limit, and the actual stock level at the time the order is made.

Optimizing transport routes is used to find the best solution as well as the time and financial savings during the supply process. The methods used to optimize transport routes can be included in the area of management of distribution systems, which include the following methods:

- Traffic problem
- Circular and delivery task:
  − Circular: The problem of the traveling salesman
- Delivery: Delivery problem

The objective of the mathematical model of the task of the business traveler is to minimize the total distance traveled by the vehicle (1) while meeting the defined conditions 1–3 [14]:

$$z = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij} \tag{1}$$

Under conditions:

$$1) \quad \sum_{i=1}^{n} x_{ij} = 1, \quad j = 1, 2, 3, \ldots. n$$

$$2) \quad \sum_{j=1}^{n} x_{ij} = 1, \quad i = 1, 2, 3, \ldots, n$$

$$3) \quad u_i - u_j + n x_{ij} \leq n - 1, \quad i = 1, 2, \ldots, n, \quad j = 2, 3, \ldots, n \quad i \neq j$$

$$x_{ij} \in \{0; 1\}, \quad i, j = 1, 2, \ldots, n; \ n \in N,$$

Capacity-constrained VRP:

$$u_i + q_j - V(1 - x_{ij}) \leq u_j$$

where:

n – number of nodes

c_{ij} – distance between nodes i and j

x_{ij} – binary travel indicator
u_i, u_j – subtour elimination
q_i – vehicle load
V – vehicle capacity

Sensitivity analysis: distances of 25, 50, 75, 100 km; ±10–30% vehicle availability; weather scenarios (sun, rain, fog).

Conditions 1 and 2 ensure that each location is visited exactly once. Condition 3 ensures that cycles do not contain a starting point [14].

The goal of the delivery problem is to satisfy the demands of all customers and return to the starting point to minimize the sum of the lengths of all routes [15].

2.2. Medical Evacuation Procedure

The purpose of medical support in military operations is to conserve manpower, preserve life, and minimize residual physical and mental disabilities. Appropriate medical support makes a major contribution to force protection and morale.

It is a responsibility of command to ensure an effective medical evacuation system is in place 24/7 and that it is capable, as far as possible, of facilitating the following activities [16]:

- Evacuate patients at day and night, in all weather and sea conditions, on any terrain and any operational circumstances
- Provide appropriate emergency and critical care throughout the evacuation
- Direct the flow of patients and their disposition to the most appropriate medical treatment facility MTF
- Track patients accurately throughout the evacuation

The robustness of the evacuation chain is directly related to and depends on the quantity and capability of the treatment assets that are required in theatre. A robust MEDEVAC system must have the following qualities [127]:

- Timeliness of treatment: Time is a fundamental factor in the effectiveness of medical care [18, 19]. Treatment and evacuation timelines in operations are determined by medical doctrines.
- Availability [20]: The aim of the medical evacuation system is to evacuate casualties 24/7 day and night, in (as far as possible) all weather and sea conditions, on any terrain and any operational circumstances.

The theatre patient evacuation policy needs to be dynamic, and it must be able to respond to changes in the operational situation according to NATO standards, such as the Golden Hour standard. The concept of the Golden Hour originates from trauma medicine and refers to the critical period immediately after an injury, within which timely surgical care substantially improves survival outcomes [21]. In the context of military operations, timely evacuation to higher medical echelons (e.g., from Role 1 to Role 2 medical facilities) is doctrinally linked to this principle, as delays beyond this timeframe correlate with increased mortality [21]. Operational research shows that rapid casualty handoff within one hour significantly reduces mortality among war-injured personnel [22]. NATO-compliant definitions are:

- Role 1: Immediate care at the unit level
- Role 2: Limited surgical and resuscitation capacity
- CASEVAC vs. MEDEVAC: CASEVAC uses non-medical transport; MEDEVAC uses equipped vehicles and trained personnel [16, 17].

The simulation incorporated triage categories (immediate, delayed, minimal, and expectant) and tracked evacuation timelines relative to the Golden Hour standard to assess evacuation performance.

3. SIMULATION

The primary objective of the simulations conducted within the MasaSword program is to analyze the impact of the logistics and medical base's distance from frontline units on the speed and efficiency of material replenishment [23, 24]. The simulation environment MasaSword is a high-fidelity constructive simulation platform widely adopted for military operational research and command staff training [25]. It is capable of representing complex interactions between combat, logistics, and support elements in large-scale scenarios, providing a controlled environment for "what-if" analyses of evacuation and resupply timelines [25]. This makes it more suitable for operational research than simple route optimization tools, as it incorporates the behavioral dynamics of units and operational doctrines rather than purely static optimization.

3.1. Settings of the Logistic Support Model Simulation

The simulation aimed to evaluate how increasing the logistics and medical base's distance affects the time to evacuate wounded personnel, based on the logical assumption that greater distances hinder the effectiveness of rescue operations. The central hypotheses are as follows:
- H1: Reducing the distance between first-line units and the medical base from 100 km to 50 km will expedite the evacuation process.
- H2: Reducing the distance between first-line units and the logistics base from 100 km to 50 km will expedite the replenishment of food and water.

According to these hypotheses, reducing the distance will enhance the overall efficiency and success of rescue efforts and the replenishment of supplies (water and food). The dispatch of logistics vehicles was triggered when stock levels fell below a predefined operational threshold, corresponding to the reorder point principle of the Q-system, traveled along the shortest available route to the destination, and returned immediately after unloading. No adaptive rerouting was allowed, ensuring consistent and reproducible routing logic across scenarios. The simulation focused on a mechanized battalion, which operates as part of a larger mechanized brigade. The observed forces are referred to as blue units, which represent the friendly battalion, while the opposing forces are designated as red units. The equipment and structure of the red units are detailed in Table 2. The following initial conditions for each simulation were set to verify the hypotheses:
- Place: Military Training Area Libavá.
- Weather: Very sunny day, no rainfall.
- Time: October 18, from 4:00 p.m.
- The organizational structure and armored technique of the blue battalion are shown in Table 1.
- The organizational structure and technique of the enemy's units are presented in Table 2.
- The numbers of transport and support equipment are shown in Table 3.
- Validation: Evacuation timelines were compared with NATO MEDEVAC doctrinal limits; routing behavior was interpreted using VRP/TSP principles.

Although the VRP and TSP models are not solved numerically within the simulation, their principles are structurally embedded in the scenario design. The logistics and evacuation vehicles repeatedly perform cyclic routes between nodes (base–frontline–base), which directly corresponds to TSP cyclic routing, while the presence of multiple vehicles serving multiple units under capacity limits reflects a practical VRP configuration. The simulation, therefore, represents an applied implementation of VRP/TSP principles in a dynamic operational environment rather than a static optimization problem. The simulation scenarios intentionally represent a baseline operational situation without route interdiction or convoy disruption. This baseline allows the isolation of transport distance to be considered a primary factor. According to risk management theory, this configuration represents the reference state against which future simulations involving route disruption, delays, or alternative routing strategies can be compared. In this sense, the model provides a controlled environment for the subsequent testing of mitigation measures and resilience strategies of the logistics-medical chain.

Table 1

Organizational structure of Blue Mechanized Brigade

Blue Mechanized Brigade	Infantry fighting vehicle [-]	Tank Leopard 2A4 [-]
1st Mechanized Battalion	39	0
2nd Mechanized Battalion	39	0
3rd Tank Battalion	X	20
4th Mechanized Battalion	39	X
Total	117	20

Table 2

Organizational structure and technique of the enemy´s units

Red forces	BTR-80 [-]	AGS -17 [-]	120mm 2S12 Sani [-]
Motorized Rifle Company	10	x	x
Motorized Rifle Company	10	x	x
Motorized Rifle Company	10	x	x
Motorized Rifle Company	10	x	x
Granade Launcher Platoon	x	6	x
Mortar Battery	x	x	9
Total	**40**	**6**	**9**

Table 3

Numbers of military logistics equipment used in the simulation

Military transport and support equipment	
Technique type	Number of techniques
Loader KTN	88
Container trailer	81
Cargo trailer	89
Trailer 04_PN-V	75
AN N3-P-transporter APH	8
AN N3-P-cis	16
Trailer 04-PN-P	17
AN N3-P-clean water	12
Trailer 03-PN-P	12
Trailer 04-PN-P	4

4. RESULTS

4.1. Wounded Personnel Evacuation

Figure 1 shows the development of the number of wounded personnel not evacuated over time for distances from 25 km to 100 km. At all distances, the number of non-evacuated wounded initially

increases, reaches a peak, and then gradually decreases as evacuation progresses (see Fig. 1). At the distance of 50 km, the first evacuation of wounded personnel took place at 17:08. The next evacuation began at 18:43. Between 18:00 and 19:00, the number of wounded soldiers dropped by 48.3%, down to 30. From that point on, the number of wounded soldiers continued to decrease until it reached zero, approximately six hours after the battle began.

At 100 km, the number rises more rapidly and remains at a higher level for a longer period. The number of wounded soldiers of the blue forces rose to 41 after an hour of fighting and never fell below the threshold of 30 soldiers. A maximum of 63 wounded personnel was recorded, representing a 53.7% increase compared to 17:00. An overview of the results is presented below:

- 25 km: Evacuation complete within four hours.
- 50 km: Evacuation complete within about six hours.
- 75 km: Evacuation complete within seven hours; 10% un-evacuated.
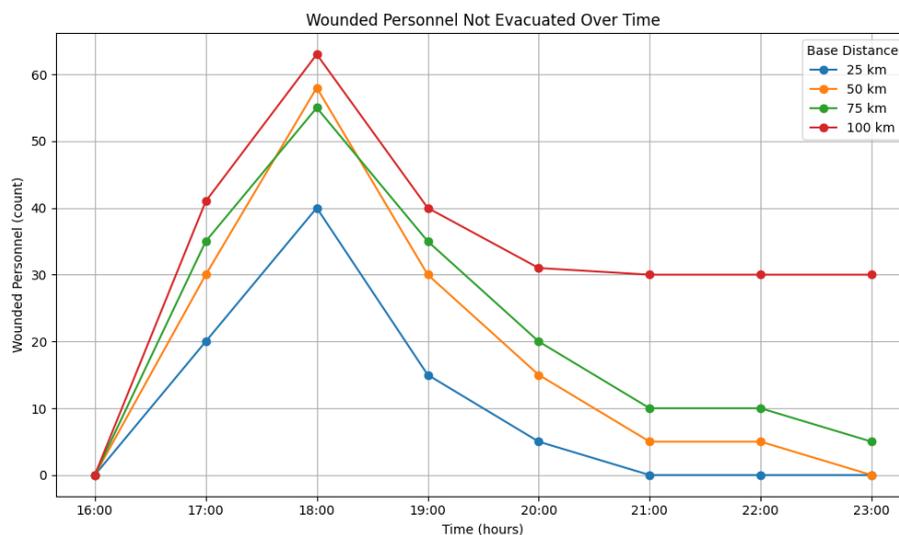- 100 km: 48% un-evacuated.

Fig. 1. Number of wounded not evacuated over distances of 25–100 km

4.2. Supply Depletion

The units of the blue battalion were supplied with food and water throughout the battle (Fig. 2), but the total stock of the blue units declined almost linearly, dropping by 26%. At the beginning of the battle, the supply level was 5190 units, but after just one hour, it dropped to 4800, representing a decrease of 7.5%. Between 20:00 and 23:00, the rate of decrease slowed, with the value remaining constant at 3860 between 21:00 and 22:00. The final value at 23:00 was 3832, indicating a total decrease of 26.1% over seven hours. An overview of the results is presented below:

- 50 km: Average 194 units/hour depletion.
- 100 km: 227.3 units/hour.
- Sensitivity: Max +12% depletion under adverse conditions.

At the start of the battle (16:00), the supply level was at 5190 units, but after just one hour, it had dropped to 4600, representing a decrease of 11.4%. This downward trend continues in the following hours by 20:00, the supply level reached 3705, which means a total decrease of 28.6% since the beginning of the battle. The overall drop in supplies from 5190 to 3599 represents a 30.7% reduction over the course of seven hours.

Table 4 presents the recorded results for wounded (not evacuated) and the status of supplies over time. Food and water supplies gradually decreased in both cases, with a more rapid decline observed at the 100-km distance. Initially, the supply levels were identical at both distances (5190 units), but over time, it became evident that values dropped more significantly at 100 km. For instance, at 19:00, the

supply level at 50 km was 4248 units, while at 100 km it was 3978 units. This trend continued until 23:00, when 3832 units remained at 50 km, compared to 3599 at 100 km. The first column (50 km) shows an average hourly decrease of 194.0 units, while the 100-km distance shows a steeper drop of 227.29 units per hour. This indicates that supply levels at 100 km decline faster than at 50 km, suggesting a higher rate of depletion and insufficient replenishment speed.
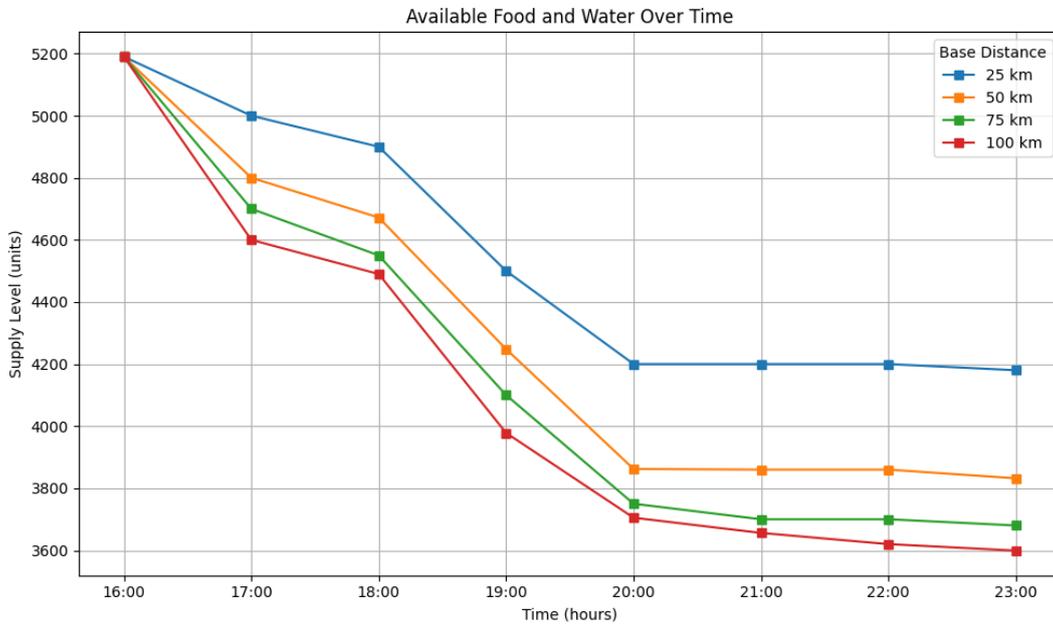

Fig. 2. Available food and water at base distances of 25–100 km

Table 4

Wounded and Supply Levels

Time	Wounded – 25 km	Wounded – 50 km	Wounded – 75 km	Wounded – 100 km	Supply – 25 km	Supply – 50 km	Supply – 75 km	Supply – 100 km
16:00	0	0	0	0	5190	5190	5190	5190
17:00	20 ↑	30 ↑	35 ↑	41 ↑	5000 ↓	4800 ↓	4700 ↓	4600 ↓
18:00	40 ↑	58 ↑	55 ↑	63 ↑	4900 ↓	4672 ↓	4550 ↓	4490 ↓
19:00	15 ↓	30 ↓	35 ↓	40 ↓	4500 ↓	4248 ↓	4100 ↓	3978 ↓
20:00	5 ↓	15 ↓	20 ↓	31 ↓	4200 ↓	3862 ↓	3750 ↓	3705 ↓
21:00	0 ↓	5 ↓	10 ↓	30 ↔	4200 ↔	3860 ↔	3700 ↔	3656 ↓
22:00	0 ↓	5 ↓	10 ↔	30 ↔	4200 ↔	3860 ↔	3700 ↔	3620 ↓
23:00	0 ↓	0 ↓	5 ↓	30 ↔	4180 ↓	3832 ↓	3680 ↓	3599 ↓

Legend: ↑ = increase, ↓ = decrease, ↔ = stable

Calculation example:
- Supply depletion at 50 km, time 16:00-17:00

$$4800 – 5190 = -390 \text{ units, Percentage} = \frac{390}{5190} \times 100 \approx 7.51\% \text{ decrease}$$

Calculation Example:
- Wounded at 50 km, time 17:00-18:00

$$58–30 = 28 \text{ wounded, Percentage} = \frac{28}{58} \times 100 \approx 48.27\% \text{ increase}$$

5. DISCUSSION

Simulations carried out in the MasaSword program with the conditions set above support the hypotheses: The further away the logistics base is, the longer it takes to evacuate the wounded. This factor can influence strategic decisions regarding the location of logistics bases and medical infrastructure in combat scenarios. From the perspective of transport systems analysis, distance is a key parameter affecting system throughput, response time, and service capacity.

In the case of medical evacuation, the simulation demonstrates a clear degradation of system performance as transport distance increases. While evacuation processes at 50 km remained within operational capacity limits and resulted in the complete evacuation of all wounded personnel, the scenario with a distance of 100 km exhibited a pronounced capacity shortfall. Nearly 48% of wounded personnel remained non-evacuated at the peak of demand, indicating that transport resources were no longer sufficient to satisfy evacuation requirements within the available time window. This outcome corresponds to congestion effects commonly observed in transport systems when demand exceeds service capacity, and it validates H1.

The logistics supply results show a comparable distance-related effect. Although supply deliveries were maintained throughout the simulation, the depletion rate increased with distance, reaching an average hourly decrease of 227.3 units at 100 km compared to 194.0 units at 50 km. This difference reflects longer transport cycles, reduced delivery frequency, and lower system responsiveness at longer distances. From a transport planning standpoint, these findings confirm H2 and illustrate how increasing route length reduces the effective replenishment rate, even when the same vehicle fleet is available.

It should be noted that the simulation model includes certain simplifications. The analysis focused on food and water supplies, while other transport-intensive commodities such as fuel and ammunition were not explicitly modeled. Additionally, transport routes were assumed to remain operational, without interdiction or dynamic rerouting. From the perspective of operations research and transport theory, the observed behavior of the evacuation and resupply system corresponds to principles known from the VRP and TSP. In classical VRP formulations, increasing the distance between nodes linearly increases travel time and reduces the number of feasible transport cycles per unit time, which directly limits the system throughput. When the demand rate (casualty generation or supply consumption) exceeds this throughput, the system reaches a capacity collapse state.

The simulation results demonstrate this phenomenon. At distances up to 50 km, the transport system was able to maintain a sufficient number of evacuation and resupply cycles. Between 75 km and 100 km, however, the system crosses a threshold beyond which the effective number of cycles per hour becomes insufficient to satisfy demand. This is consistent with VRP theory, which states that route extension under capacity constraints leads to a non-linear degradation of service performance rather than a simple proportional delay.

In the context of medical evacuation, this transport capacity threshold has a direct doctrinal implication related to the NATO Golden Hour. The simulation indicates that at 100 km, evacuation timelines exceed this doctrinal window despite full vehicle availability, meaning that the limitation is not organizational but transport-capacity-driven. This finding links transport modeling with medical doctrine and shows that base placement decisions can determine whether doctrinal standards are achievable. Therefore, the results should not be interpreted merely as evidence that a longer distance causes delays but rather as identification of a distance-dependent capacity threshold of the logistics and evacuation network.

Given that military evacuation and logistics systems are subject to uncertainty in transit times, demand levels, and environmental conditions, a sensitivity analysis was conducted on key parameters. Specifically, simulation runs varied vehicle speed assumptions, casualty generation rates, and evacuation destination distances to observe their impact on evacuation completion times and throughput. The results demonstrate that increased distance and reduced fleet availability have non-linear impacts on evacuation latency, validating the operational sensitivity of the modeled system. Although formal probabilistic uncertainty modeling (e.g., Monte Carlo simulations or stochastic VRP frameworks) was not implemented, the explicit sensitivity analysis highlights key thresholds at which evacuation

timelines exceed doctrinally relevant benchmarks, such as the Golden Hour constraints, reinforcing the robustness of findings across plausible operational ranges.

Overall, this study highlights that transport distance is a critical constraint on evacuation and resupply systems and that simulation-based methods are well-suited for identifying distance thresholds at which transport capacity becomes insufficient.

6. CONCLUSIONS

This study applied a simulation-based approach to analyze transport-dependent processes in military logistics, focusing on casualty evacuation and supply replenishment under varying distance scenarios. The results demonstrate that the transport distance between combat units and logistics or medical bases has a significant and measurable impact on system performance.

For medical evacuation, increasing the distance from 50 km to 100 km resulted in a transition from full system effectiveness to a situation in which transport capacity was insufficient to meet evacuation demand. Similarly, supply transport at longer distances exhibited higher depletion rates due to slower replenishment cycles, despite continuous delivery attempts. These findings confirm that distance is a dominant factor influencing evacuation efficiency and supply sustainability.

From a broader transport research perspective, the presented methodology is not limited to military applications. The simulation framework enables the evaluation of transport capacity, time constraints, and resource allocation in systems characterized by uncertain demand and limited infrastructure. This makes the approach applicable to other domains involving emergency logistics, crisis response, or remote-area supply chains.

Overall, the conclusions provide valuable insights that can be useful to military planners and strategic decision-makers in the planning of specific combat operations and in the development of supply and logistics strategies in combat. In addition to the advantages mentioned above, simulations involving logistics and medical chains can obtain alternative and backup solutions, reduce risk, and save staff capacity and time.

A significant portion of the budget of the Ministry of Defence is intended to finance intangible forms of logistic support, and that is the provision of logistics services. Not performing simulations could result in a failure to achieve the objectives of operations and waste the ministry's budget. At the same time, it is necessary to carry out simulations, evaluate them critically, and be flexible in adapting to changing circumstances and the systematic development of knowledge on how best to counteract threats based on simulation.

A strategic trade-off must be considered when interpreting the simulation results presented in this paper. While shorter distances significantly improve evacuation and resupply efficiency, locating logistics and medical bases closer to frontline units may increase their exposure to enemy action. Therefore, the presented results provide a quantitative basis for balancing transport efficiency against operational vulnerability, an aspect that can be further explored in future simulations including risk scenarios.

Future research should extend the model by incorporating additional transport commodities, adaptive routing strategies, and higher-echelon formations to improve scalability and external validity. The inclusion of stochastic disruptions to transport routes would further enhance the realism of the model and its relevance for transport system resilience analysis.

In conclusion, the present study confirms that simulation-based transport analysis is a valuable decision-support tool for assessing the performance limits of logistics and evacuation systems under varying distance and capacity conditions, aligning well with the analytical scope of transport-oriented research.

Acknowledgment

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