MEDEVAC Mission Planning and Decision Making with Mixed-Integer Programming and Wargaming

Armin Fügenschuh
Brandenburg University of Technology, Institute for Mathematics
Platz der Deutschen Einheit 1, D-03046 Cottbus
GERMANY

fuegenschuh@b-tu.de

ABSTRACT

In the highly dynamic environment of military operations, efficient medical evacuation (MEDEVAC) of casualties is a critical strategic challenge. This paper presents a method for planning MEDEVAC missions using mathematical optimization and gamification. By applying Mixed-Integer Programming (MIP), a mathematical optimization technique, to solve a MEDEVAC dispatching and routing problem, a structured approach to decision making in emergency situations is presented. Our MIP model enables the detailed consideration of operational conditions and the mission support with combat helicopters as escorts, and thus improves the strategic planning and efficiency of MEDEVAC operations. When it comes to balance mission safety versus execution speed, we will enter the realm of multicriteria optimization models. As a further aspect, the role of gamification is emphasized by developing a board game that simulates the planning task and thus promotes understanding of the planning software. This approach allows planners to compare the quality of their manual planning with the computer-generated solution, improve their own planning skills and realize the benefits of software support for automated, AI- (Artificial Intelligence-) -assisted planning.

KEYWORDS

Medical Evacuation (MEDEVAC) Planning, Mixed-Integer Programming (MIP), Decision Making, Multicriteria Optimization, Gamification.

1.0 INTRODUCTION

In the unpredictable realm of military operations, providing timely and efficient medical care for wounded personnel is a strategic necessity. Modern armies engaged in combat operations must ensure the rapid and secure transportation of injured personnel from casualty collection points (CCPs) or Role 1 facilities to field hospitals (Role 2). This early stage of the MEDEVAC chain is crucial for initiating intensive medical treatment, thereby reducing fatalities and the need for amputations. Helicopters equipped for MEDEVAC are often the primary mode of transportation. These helicopters are equipped to monitor vital functions and initiate critical measures to stabilize patients. They are quick, flexible, and not dependent on roads, making them less susceptible to threats like landmines. However, their vulnerability in high-threat environments necessitates the support of armed escorts, such as combat helicopters. The challenge of MEDEVAC planning is further compounded by resource limitations and the multitude of demands, necessitating effective prioritization. Balancing the need for rapid evacuation with the safety of MEDEVAC crews involves complex decision-making that must integrate ethical principles to ensure just and humane treatment of all personnel. To address these challenges, this paper proposes the application of mathematical optimization methods, specifically MIP, for MEDEVAC mission planning. By formalizing requirements and defining variables, constraints, and objective functions, the paper aims to balance the safety of MEDEVAC crews with the goal of rescuing as many wounded personnel as possible through multi-objective optimization techniques. Additionally, the use of wargaming, through the development of a board game that simulates MEDEVAC planning, can enhance understanding and skills among planners. This gamification approach allows for the comparison of manual planning with computer-generated solutions, highlighting the benefits of automated, AI-assisted planning.

The remainder of this paper is structured as follows. Chapter 2 provides a literature review and positions our contribution within the existing body of research. Chapter 3 discusses the challenges and requirements for efficient MEDEVAC planning, highlighting strategic and tactical considerations. Chapter 4 presents the methodology, including the formulation of the MIP model, with detailed explanations of the sets, parameters, variables, objective function, and constraints used. Chapter 5 features a case study, describing the input data, the numerical solution process, and the results obtained. Chapter 6 explores the potentials of gamification in MEDEVAC planning, detailing the motivation and background behind this approach and outlining the rules and gameplay of a MEDEVAC CoSim board game. Chapter 7 concludes the paper with a summary of key findings, implications for practice, and directions for future research and technological developments. Finally, Chapter 8 lists the references cited throughout the paper.

2.0 LITERATURE REVIEW AND POSITIONING OF OWN CONTRIBUTION

In the literature survey of military MEDEVAC operations [1], [2], [3], it becomes apparent that distinct mathematical techniques are employed to address two primary subproblems within this domain: the location-allocation problem and the dispatching problem. Each problem requires a specialized approach due to its unique characteristics and challenges. For the location-allocation problem, MIP is utilized [4], [5]. This problem involves determining the optimal placement of helicopter staging facilities and medical treatment facilities (MTFs), along with the allocation of helicopters to these facilities. MIP models are particularly suitable for this problem as they effectively handle discrete decision variables and complex constraints. They provide solutions that optimize the layout of MEDEVAC assets, considering factors such as resource limitations, geographical considerations, and operational requirements. The use of MIP in this context ensures that MEDEVAC systems are designed to maximize efficiency and effectiveness in a deployed environment. The dispatching problem, which focuses on selecting the appropriate MEDEVAC unit in response to service requests, can be approached through the lens of Markov decision processes (MDPs) [6] and approximate dynamic programming (ADP) [7]. This problem is inherently dynamic and involves decision-making under uncertainty, making MDPs an ideal framework for modeling the sequential and stochastic nature of dispatching decisions. ADP and related techniques, such as reinforcement learning, are employed to address the computational challenges posed by large-scale MDPs. These methods enable the development of robust dispatching policies by approximating value functions and iteratively refining decision strategies. Kearby et al. [8] investigate the complexities of noncombatant evacuation operations, which present unique challenges due to the large scale and dispersed nature of the population. They develop a time-staged network model using an MIP to optimize evacuation flows and minimize completion time, taking into account the capacity and resource constraints of various transportation modes. Their model allocates limited assets across a time-staged network, resulting in a feasible evacuation plan that is further refined into a high-resolution schedule for each asset. Lejeune and Margot [9] introduce a mixed-integer nonlinear MEDEVAC model that integrates endogenous uncertainty in casualty delivery times to ensure timely medical treatment via air ambulances. The model optimizes the locations of MTFs and air ambulances, and their dispatch to injury points, considering the Golden Hour[1] doctrine and air ambulance availability.

Our paper deals specifically with a variant of the military MEDEVAC dispatching problem, and explores an approach and methodology to optimize the decision-making process in MEDEVAC operations. This focus aligns with the current research trend in military operations research, particularly in the context of high-intensity combat operations where efficient and rapid response is crucial for casualty survival. As a novel contribution, we introduce the use of MIP to the military MEDEVAC dispatching and routing problem,

[1] The Golden Hour doctrine in MEDEVAC refers to the critical one-hour window in which severely injured personnel should receive definitive care to improve survival rates. [10]

diverging from the traditional approaches of MDPs and ADPs. While MDP and ADP are effective in developing optimal policies for dispatching under uncertainty, they primarily focus on high-level strategies rather than detailed operational planning. These methodologies yield policies that dictate which MEDEVAC unit to dispatch based on the system's current state, optimizing objectives like response time and casualty evacuation efficiency. In contrast, our MIP approach provides a structured and deterministic framework that enables the incorporation of detailed operational constraints and discrete decision variables. This allows for the formulation of specific tasks and routes for MEDEVAC units, addressing logistical and tactical aspects of dispatching in a comprehensive manner.

The presented MEDEVAC dispatching and routing MIP model has notable similarities to the work of Fügenschuh, Nemhauser, and Zeng [11] on scheduling and routing small planes for fly-in safaris. Both problems involve the transportation of individuals—tourists in the earlier work and wounded personnel in the MEDEVAC context—using aerial vehicles that can make multiple intermediate stops for pick-up and drop-off. In both scenarios, the vehicles must adhere to time windows and capacity constraints, and refueling logistics are critical considerations. The mathematical models underlying both problems utilize a flow-over-flow formulation on a time-expanded graph network to optimize routing and scheduling. A significant difference in the MEDEVAC problem is the inclusion of combat helicopters for escorting, adding another layer of complexity. Despite these differences, the core methodological approach of utilizing advanced optimization techniques to address scheduling and routing challenges in a dynamic environment remains a shared aspect of both studies.

3.0 CHALLANGES AND REQUIREMENTS IN MEDEVAC

In modern warfare, efficient MEDEVAC is crucial for enhancing survival rates and reducing long-term disabilities among injured soldiers. Role 2 MTFs, as defined by NATO, provide advanced trauma management and emergency surgery. These facilities are typically positioned 40 to 60 kilometers from the frontline to balance timely medical intervention with safety from enemy artillery. A brigade generally operates one Role 2 MTF, designed to handle 10 to 20 patients simultaneously, with the capacity to treat multiple patients sequentially over a 72-hour period. The locations of these facilities are assumed to be predetermined for this model, and scenarios involving multiple Role 2 MTFs are considered to reflect complex operational environments.

In combat scenarios, soldiers can suffer severe injuries such as gunshot wounds, explosion injuries, burns, traumatic brain injuries, and hemorrhagic shock. Post-combat, injured soldiers are transported to CCPs or Role 1 facilities for initial treatment before evacuation to Role 2 MTFs. In cases of multiple casualties, triage levels—Immediate, Delayed, Minimal, and Expectant—are used to prioritize treatment based on injury severity and survival likelihood.

Several helicopter types are used worldwide for MEDEVAC missions, each equipped to transport multiple stretcher patients and provide advanced medical care during evacuation. A typical MEDEVAC helicopter can carry 2-6 stretcher patients and is outfitted with modern medical and flight systems to ensure efficient and safe patient transport. To protect these missions in high-threat environments, combat helicopters often provide escort, equipped with advanced weaponry and sensor systems to neutralize threats and safeguard the operation. MEDEVAC helicopters have a certain operational range, for example 800 kilometers, allowing for rapid patient transport over significant distances. The combat helicopters providing escort typically have a similar range, ensuring they can effectively accompany MEDEVAC missions without the need for immediate refueling. However, refueling remains a critical consideration in mission planning, particularly for extended operations. Planners must identify potential refueling points or consider using auxiliary fuel tanks to extend the helicopters' range. Factoring in refueling needs ensures continuous operation and timely MEDEVAC, which is crucial in dynamic combat situations.

MEDEVAC mission planning involves collaboration among medical personnel, MEDEVAC coordinators, and higher command centers. Medical personnel assess and prioritize casualties, while coordinators allocate helicopter resources. Higher command oversees operations, ensuring alignment with broader objectives and deciding on combat helicopter support based on threat assessments. Our mathematical model addresses the MEDEVAC mission planning problem, assuming fixed locations of Role 2 MTFs. After a battle, injured soldiers at various points along the frontline and CCPs need transport to Role 2 MTFs using a fleet of helicopters. The goal is to optimize helicopter routes and prioritize casualties based on medical urgency, enhancing MEDEVAC operations' overall effectiveness. The model focuses on the initial evacuation from the frontline to Role 2 facilities, without incorporating transport from Role 2 to Role 3/4 MTFs, which is beyond the scope of our planning model.

4.0 METHODOLOGY

4.1 Model Formulation

The mathematical model for planning MEDEVAC missions is formulated as a MIP. In its general abstract form, a MIP can be described as follows: $\min \{cx \mid Ax \leq b, x \geq 0, x \in \mathbb{Q}^p \times \mathbb{Z}^q\}$. Here, the finite and nonempty set of integer variables (in $\mathbb{Z}$) is represented by q, while the finite and nonempty set of rational variables (in $\mathbb{Q}$) is given by p, with p and q being disjoint. If p is empty, then there are no rational variables, which results in a pure integer linear program. Conversely, if q is empty, then there are no integer variables, which results in a pure linear program. This latter case is important in the solution process for MIPs, as discussed in Section 5.2. As abbreviation, let $n := p \cup q$. Let m denote the given finite, nonempty set of constraints.

Besides the sets, the model is further defined by the given parameters, specified by the vector $c \in \mathbb{Q}^n$ of the objective function coefficients, the constraint coefficient matrix $A \in \mathbb{Q}^{n \times m}$, and the vector of the right-hand side values $b \in \mathbb{Q}^m$.

The vector $x \in \mathbb{Q}^p \times \mathbb{Z}^q$ contains the decision variables. These are the unknowns that need to be computed, and that describe a feasible solution, if $Ax \leq b, x \geq 0$ is fulfilled. If x^* is a feasible solution with $cx^* \leq cx$ for all feasible solutions x, then x^* is called an optimal solution for the minimization problem.

To apply this abstract setting to the MEDEVAC dispatching and routing problem, we need to specify the given data (A, b, c, m, p, q) accordingly. The following sections describe this specification in detail, focusing on the practical aspects of the problem without delving into all the algebraic details. Each entity in the model is highlighted by *italic* letters.

4.1.1 Sets

In the mathematical model for planning MEDEVAC missions, the abstract sets m, p, q are specified by several sets that are defined to represent various elements of the problem, capturing key aspects of the operations.

The set of *nodes* includes all points of interest within the operational area, such as the battlefield, the base (Hub), CCPs, MTFs, and intermediate nodes used for longer flight trajectories. The battlefield is where soldiers emerge, and the Hub is where all helicopters start and end their missions and can refuel. The CCPs (which here also subsume Role 1 facilities) are the locations where wounded soldiers are initially gathered and triaged before being evacuated by MEDEVAC helicopters. As can be seen in Figure 1, each MTF node has two associated subnodes: one for patient treatment (called MTFX) and one for helicopter landing zones, representing the treatment and logistical capabilities of the MTFs. Intermediate nodes are used to model longer flight trajectories for the helicopters, allowing for a more detailed and realistic representation of the evacuation routes. The set of *arcs* consists of all possible routes or connections between adjacent nodes in the network, capturing the potential flight paths that helicopters and patients can take during the evacuation process. A subset of these routes includes only those feasible for helicopter travel, excluding direct connections to and from the battlefield and patient areas in MTFs. Together, nodes and arcs define a graph. *Time steps* are used to synchronize operations, with discrete steps modeling the timing of events and movements within the MEDEVAC mission. Several sets of time steps are defined to capture the beginning, intermediate, and end of the mission timeline. Combining the time steps with the node-arc graph results in a time-expanded graph, which serves as the underlying structure for all operations in the model.

The set of *MEDEVAC helicopters* includes all the helicopters used for transporting wounded soldiers from CCPs to MTFs. The set of *combat support helicopters* (CSHs) represents the helicopters which provide escort and protection for the MEDEVAC helicopters, especially in high-threat areas. *Threat levels* are used to assess the risk and security requirements for MEDEVAC missions in different parts of the operational environment. The set of *patients* encompasses all individuals who require evacuation and medical attention during the mission. Finally, the *objective function weights* are used to quantify and prioritize different objectives within the model, such as minimizing evacuation time or maximizing the number of patients evacuated.

4.1.2 Parameters

The parameters that can be found in A, b, c in the mathematical model for planning MEDEVAC missions capture specific characteristics and constraints of the problem.

Objective function weight parameters allow for the prioritization of different objectives within the model, enabling a tailored approach to optimizing MEDEVAC mission planning, toggling the emphasis between MEDEVAC safety and fast evacuation. The *capacity* of each MEDEVAC helicopter specifies the number of patients it can carry, which can vary based on the helicopter's type and its respective configuration. The *refueling* parameter indicates the number of time steps before each MEDEVAC helicopter requires refueling, modeling the operational range and mission duration.

Patient locations identify the initial location of each patient at a CCP before evacuation. The *urgency* parameter denotes the urgency of each patient, with a scale indicating their survival duration. Higher values represent a more urgent need for transportation and treatment, which is used for triaging and prioritizing patients. The *earliest transport time* specifies the earliest time each patient can be transported from the CCP, setting a lower bound on the departure time for evacuation. Conversely, the *latest arrival time* defines the latest time each patient should arrive at an MTF, ensuring timely medical treatment. The *space required* in the helicopter for each patient, based on whether the patient is seated or requires lying down, affects how many patients can be transported simultaneously. The *treatment capacity* at each field hospital defines the number of injured patients that can be treated simultaneously, while the *resource consumption* parameter represents the medical resources needed for each patient's treatment at a field hospital.

The *fire risk* parameter reflects the expected risk of being under fire in unsecured areas, quantifying the danger associated with specific locations and routes. The *route risk class* specifies the risk level associated with each route in the network, representing the danger or difficulty of traversing certain paths. *CSH protection* indicates the percentage reduction in fire risk when a CSH is present, assessing the protective effect of these helicopters. The *refueling* parameter for CSHs denotes the number of time steps until each CSH requires refueling, influencing their operational range and mission duration.

Finally, the *time horizon* sets the end of the finite time period for the model, within which the MEDEVAC missions are planned and executed. Each *time step* represents a specific duration in real time, such as 5 or 10 minutes.

4.1.3 Variables

In the mathematical model developed for planning MEDEVAC missions, decision variables x are defined to capture the dynamic aspects of operations. These variables represent the interactions between helicopters, patients, and the operational environment.

The *MEDEVAC Helicopter Flight Movement* variable indicates whether a MEDEVAC helicopter is flying along a specific route segment at a particular time step. These binary variables capture the flight paths of the helicopters during the mission, ensuring that their movements are accurately represented.

The *CSH Flight Movement* variable represents the flight movements of CSHs. These binary variables indicate the presence of CSHs along specific route segments at given times, ensuring that their role in providing escort and protection is properly accounted for in the mission plan.

The *Patient Movement* variables indicate whether a patient is being transported by a specific MEDEVAC helicopter along a particular route segment at a given time. These binary variables track the locations and movements of patients throughout the evacuation process. Additionally, they can account for patient movements on certain routes without helicopter transport, providing a comprehensive view of patient logistics.

The *Risk* variable represents the risk associated with each flight segment for MEDEVAC helicopters. These non-negative variables quantify the danger of flying through specific routes or operating in certain locations at particular times, allowing the model to incorporate risk mitigation strategies into the planning process.

4.1.4 Objective Function

The objective function c in our model aims to balance two conflicting aspects of MEDEVAC operations: maximizing the effectiveness of patient care and minimizing the risks associated with the missions.

The first objective focuses on maximizing the duration of patient care within field hospitals, prioritized by the urgency of their medical needs. This involves optimizing the allocation of patients to MEDEVAC helicopters and subsequently to field hospitals, ensuring that the most critically injured patients are transported and treated promptly. The objective assigns higher priority to patients with greater urgency, promoting swift evacuation for those who need immediate medical attention.

The second objective aims to minimize the mission risk for MEDEVAC helicopters. It calculates the risk associated with each flight segment and aggregates these risks to assess the overall mission risk. Lowering this risk is crucial for ensuring the safety of both the patients and the MEDEVAC crew. This involves considering the dangers of flying through specific routes and operating in certain areas, and reducing these risks through careful planning and the use of CSHs.

By combining these two objectives using user-defined weights, the model seeks to find an optimal balance between rapid patient evacuation and conducting MEDEVAC missions under acceptable risk levels. The weights assigned to each objective allow for the prioritization of patient care or risk minimization based on the specific requirements and constraints of the mission. This balanced approach ensures that the MEDEVAC operations are both effective in saving lives and safe for the medical crews involved.

4.1.5 Constraints

The constraints, encoded in A and b in our model, ensure that MEDEVAC operations adhere to resource limitations, operational requirements, and safety considerations. They capture key aspects of mission planning, such as helicopter movements, patient transport, hospital capacity, refueling needs, and risk mitigation.

4.1.5.1 MEDEVAC Helicopter Flight Movement

First, each MEDEVAC helicopter must begin its mission from the base at the initial time step. MEDEVAC helicopters are prevented from starting their flights from any location other than the base at the initial time step. To maintain logical and continuous paths for the helicopters, the model requires that for every flight segment entering a node, there is a corresponding flight segment leaving the node in the next time step. Lastly, each MEDEVAC helicopter must return to the base by the end of the mission.

4.1.5.2 CSH Flight Movement

Similar constraints are applied to CSHs. Each CSH must start its mission from the base at the initial time step. CSHs are also prevented from starting their flights from any location other than the base initially. The model ensures that CSHs maintain a continuous path by linking incoming and outgoing flight segments at each node, similar to MEDEVAC helicopters. Each CSH must return to the base by the end of the mission.

4.1.5.3 Patient Movement

Each patient begins at their designated CCP or battlefield at the initial time step, ensuring that all patients are correctly accounted for at the start. It has to be made sure by further constraints that patients are not assigned to CCPs other than their designated ones for evacuation. Patients are not evacuated before their earliest possible departure time, ensuring that initial medical treatments at the CCP are completed. Patients must arrive at an MTF no later than their latest allowable time, ensuring timely medical intervention. Patients cannot begin their evacuation from locations other than the battlefield initially. The model ensures patients disembark at the correct time step. Lastly, continuity in patient movement is ensured by linking incoming and outgoing segments of patient transport at each node.

4.1.5.4 Coupling Patient and Helicopter Movement

Patients can only be transported on routes where a helicopter is present. Additionally, the total space occupied by patients in a helicopter must not exceed the helicopter’s capacity, ensuring effective use of resources and preventing overloading.

4.1.5.5 Field Hospital Capacity

The resource consumption by patients in a field hospital at any given time must not exceed the hospital’s treatment capacity. This ensures that hospitals are not overwhelmed and can provide adequate care to all incoming patients.

4.1.5.6 Refueling

Each MEDEVAC helicopter must return to the base for refueling within its operational time frame, ensuring that helicopters have the necessary fuel for their missions and can continue operating without interruptions. Similarly, CSHs must also return to the base for refueling, ensuring their continuous operational capability and effectiveness in providing escort.

4.1.5.7 Risk Reduction with CSH Escort

The model calculates the risk associated with enemy contact for MEDEVAC helicopters and accounts for the reduction in this risk when escorted by CSHs. This ensures that the safety of the evacuation missions is maximized, especially in high-threat areas.

5.0 CASE STUDY AND RESULTS

5.1 Model Input Data

A test scenario is depicted in Figure 1, showing a map consisting of nine hexagonal fields, each with a diameter of approximately 20 km. This scenario is entirely fictional and has no relation to any real-world situation. With a flying speed of 240 km/h, it takes about 5 minutes to move from one hex field to the next, so the time step duration is set to 5 minutes. The time horizon is set to 48 time steps, i.e., a total mission duration of 4 hours.

The map includes two Role 2 MTFs (called MTF1 and MTF2). Each of them has a capacity of 15 normal care patients or 5 high care patients. For simplicity, we assume that a high care patient consumes 3 times the resources of a normal care patient. The hex field of each MTF is divided into two sections: one for the landing zone of the MEDEVAC helicopters and the other for the treatment area (MTFX1 and MTFX2). Additionally, there are three intermediate nodes (I1-3) and three CCPs (called CCP1-3). All helicopters are stationed at the Hub, where they begin and end their missions. This Hub also serves as a refueling point.

There are two MEDEVAC helicopters and one CSH, all initially fully fueled. The helicopters have a range of 720 km, which in the model translate to a refueling after at most 36 time steps. The risk associated with flying from one hex to the next, as well as staying in one area, is indicated by the color of the arrows on the map. Each color corresponds to a specific risk level for the MEDEVAC helicopters, and this risk can be reduced by the presence of CSHs. The actual risk values are detailed in Table 1.

Initially, several wounded personnel are awaiting transport at the CCPs. They have been triaged, with the duration they can wait before transport and the urgency of their evacuation outlined in Table 2. The patient must reach any MTF within the given time limit (latest time step since the beginning), and the urgency value λ gives a "bonus" of 10^{λ} for each time step the patient arrives before that at an MTF. If depicted in an upright position, the patient can be transported seated and requires only one seat; otherwise, they must be transported lying down, occupying the equivalent of three seats in the MEDEVAC.

The objective is to deploy the helicopters to collect all casualties, transport them to an MTF with available capacity, and complete the mission with minimum risk and in the shortest possible time. Since this is a multi-criteria problem, we need to establish a hierarchy for the objective functions. Our primary focus is on the quick and complete evacuation of all casualties, even if it involves taking higher risks. However, it is possible to adjust the weights in the objective function to prioritize the safety of the MEDEVAC helicopters. Doing so would lower the risk, but it may result in slower evacuation due to waiting for the single CSH, and potentially not all casualties being evacuated in the end.

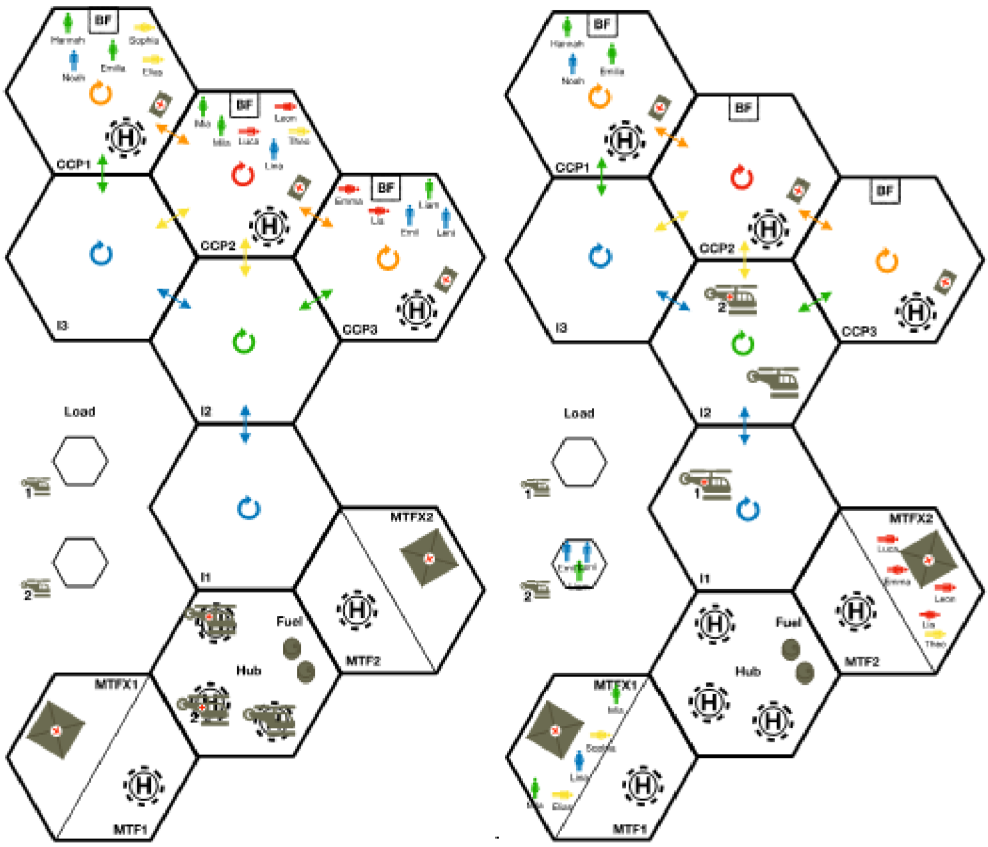

Figure 1: A test scenario. Left: Initial state at t = 0. Right: At state t = 28.

Table 1: Risk levels for MEDEVAC routes and mitigation by CSHs.

symbol	color	w/o CSH	with 1 CSH	with 2 CSH
	white/none	0 %	0 %	0 %
	blue	1 %	0 %	0 %
	green	2 %	0 %	0 %
	yellow	3 %	0 %	0 %
	orange	8 %	3 %	0 %
	red	10 %	5 %	0 %

Table 2: Triage levels and details.

symbol	color	meaning	last time step	urgency	seats	MTF cap.
	black	dead	999	0	3	1
	blue	expected	999	1	3	3
	green	minimal	48	2	1	1
	yellow	delayed	24	3	3	3
	red	immediate	12	4	3	3

5.2 Numerical Solution Process and Results

Since the model is formulated as a MIP, it can be solved using a branch-and-cut approach. In this method, the integrality constraints on the model's variables are initially relaxed, converting the problem into a linear programming problem. The integrality is then reintroduced by branching on fractional variables. Additionally, extra linear constraints, known as cutting planes, are added to the model's formulation to eliminate infeasible fractional solutions. The mathematical details of this procedure are extensively covered in the textbook by Nemhauser and Wolsey [12]. Numerical implementations of this approach are available in various software packages. In our numerical experiment to solve the test instance to proven global optimality, we used Gurobi v11.0.0 [13] on a MacBookPro 2023 laptop with an Apple M2 Max CPU[2] and 96 GB of RAM[3]. An initial feasible solution was found after 4 seconds, and an optimal solution was computed after 22 seconds. In Figure 2, we present the objective function values of several solutions from the Pareto front, demonstrating the trade-offs between the two objectives: the number of evacuated casualties and the associated mission risk. The human planner must decide whether to prioritize the maximum evacuation of casualties, minimize mission risk, or find a balance between the two. The figure illustrates that if a risk-averse approach is adopted, no flights are conducted, and consequently, no individuals are evacuated. As the number of evacuated persons increases, so does the mission risk. For instance, the data shows that evacuating all 16 casualties results in a mission risk exceeding 80%. This risk is calculated as the aggregate risk from each flight operation over the hex fields. The final selected solution from the Pareto front specifies the detailed logistics of casualty pickups at the front line, the MTFs they are transported to, and the CSHs' flight operations.

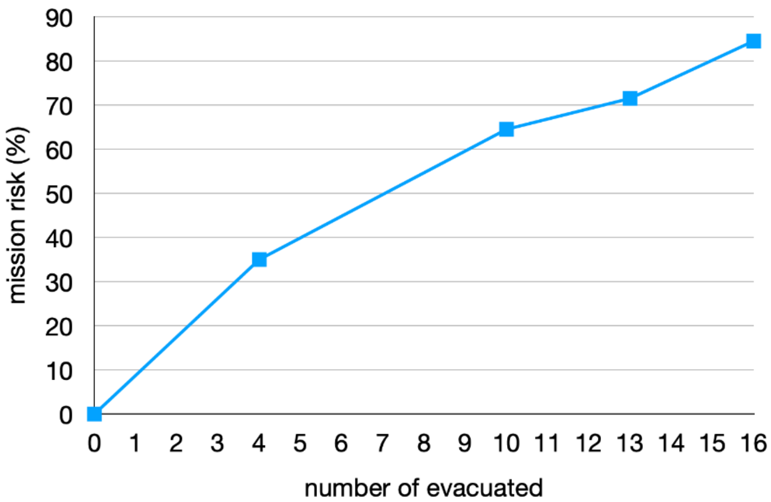

Figure 2: Trade-off between the number of evacuated casualties and mission risk.

6.0 THE POTENTIALS OF GAMIFICATION IN MEDEVAC PLANNING

6.1 Motivation and Background

The use of mathematical models for planning tasks in military operations requires users to relinquish a degree of control to a computational system. These systems generate scientifically grounded solutions that may not always be intuitive or transparent to the users. Furthermore, planners must be prepared for scenarios where the computational tools are unavailable, yet the mission must still be executed. This creates a tension between

[2] CPU: Central Processing Unit

[3] RAM: Random-Access Memory

familiarizing planners with software support and ensuring they do not become overly dependent on it. To address this, gamification offers a valuable educational tool. By embedding the planning task within an analog board game (wargame), players—potential future MEDEVAC planners—can engage with the scenarios both with and without computational assistance. This allows them to compare their own strategies with those derived from the model, enhancing their understanding and improving their planning skills.

In a previous application involving mission planning for Unmanned Aerial Vehicles (UAVs), a board game was developed [14] to simulate the task of locating insurgents planning a surprise attack at a known time and place, though the specific route to the target was unknown. The player had to decide the drone's flight path to intercept the insurgents quickly, with hidden movements controlled by an umpire. The umpire's role was crucial in assessing the mission's success, simulating realistic challenges faced by drone operators and helping players understand the complexity of mission planning under uncertainty and limited information.

As the game progressed over multiple rounds, players developed better strategies, improving their decision-making skills. In a variant of the game, players were provided with computer-generated flight path suggestions. This model was tailored to the game's context [15], and players could choose to follow or disregard these suggestions. The subsequent debriefing sessions highlighted the differences between human and computer-generated decisions, fostering an appreciation for algorithmic solutions and enhancing understanding of both approaches—human intuition and machine-assisted optimization. For further details on this approach we refer to [16].

In this ongoing project, we are adapting these concepts to MEDEVAC mission planning. This adaptation aims to bridge the gap between theoretical optimization models and practical application in military operations. While real-world testing with participants has not yet been conducted, the experience from the UAV board game suggests that gamification can be a powerful educational tool. It encourages creative and tactical thinking, helping players to recognize the strengths and limitations of both human and computational decision-making processes. By fostering a deeper understanding and trust in the technologies used, gamification could play a crucial role in enhancing the training and preparedness of military personnel involved in MEDEVAC operations.

6.2 Rules and Gameplay of the MEDEVAC CoSim Boardgame

The MEDEVAC CoSim boardgame simulates the planning and execution of MEDEVAC missions, with the objective of safely evacuating casualties from the battlefield to MTFs while minimizing risks and optimizing resource use. The game provides an educational platform for understanding the complexities of MEDEVAC planning, including triage, resource allocation, and the use of CSHs for protection.

The game board features a hexagonal grid map representing key locations such as the battlefield, CCPs, MTFs, intermediate nodes, and a Hub for helicopters. Tokens represent MEDEVAC helicopters and combat helicopters, while casualty tokens denote wounded soldiers categorized by triage levels (Immediate, Delayed, Minimal, Non-Urgent, Expectant). Risk markers are used to indicate varying threat levels in different hexes, and action cards introduce special events or challenges that can affect the mission. The game also includes a time track to manage turns and time-sensitive actions, and player sheets for tracking resources, helicopter status (current capacity, fuel), and casualty details.

The game setup involves placing the Hub, MTFs, CCPs, and intermediate nodes on the game board according to the scenario layout. Helicopter tokens are placed at the Hub, and casualty tokens are distributed at CCPs based on the scenario, each assigned a triage level. Risk markers are placed in hexes to represent threat levels, and the game turn counter is set to the starting position. Figure 3 shows a potential initial setup.

Gameplay is turn-based, with each turn representing a fixed time increment, such as 5 minutes. The game is designed for a single player, with an umpire available to ensure rules are followed and to update counters, allowing the player to focus on decision-making. The game consists of several phases.

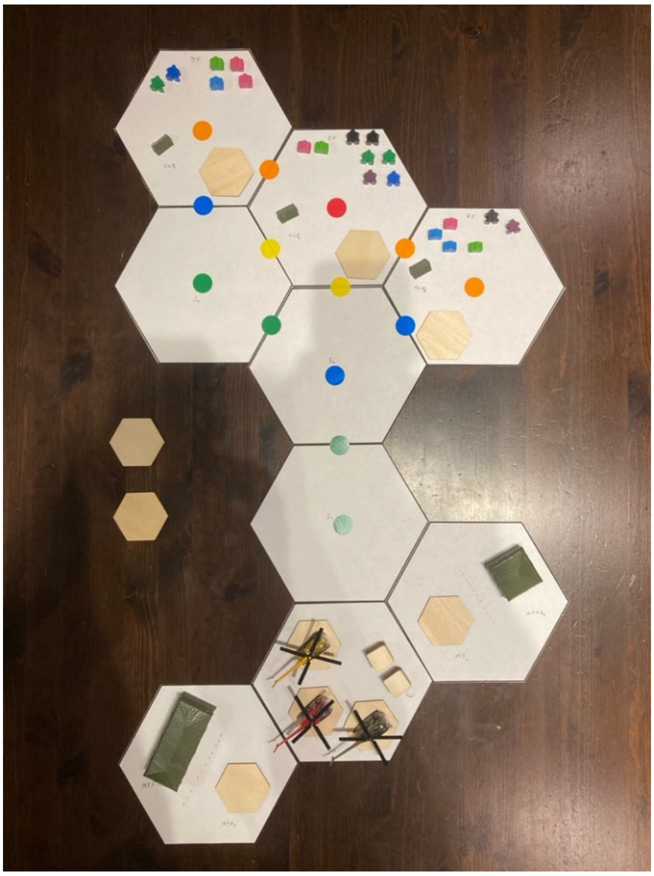

Figure 3: The board of the tabletop CoSim wargame for MEDEVAC operations.

In the *Planning Phase*, the player decides which casualties to prioritize for evacuation, considering triage levels and the urgency of medical needs. Helicopters are assigned to specific missions, with routes planned according to fuel limits and risk levels. During the *Movement Phase*, the player moves helicopter tokens according to the planned routes, consuming fuel and progressing time. CSHs can be deployed to reduce risk levels along routes or at specific locations. In the *Evacuation Phase*, the player manages the transport of casualties from CCPs to MTFs, ensuring that patients arrive at MTFs within critical timeframes while managing helicopter capacity and patient conditions. The player must also track fuel consumption and helicopter readiness, returning helicopters to the Hub for refueling and maintenance as needed. The *Event Phase* introduces action cards that create unexpected challenges or opportunities, such as changing weather conditions or new threats. Risk markers are adjusted based on the current game state, reflecting changes in threat levels in certain areas. In the *Debriefing Phase*, the player assesses the outcomes of the mission. Points are awarded based on the number of casualties evacuated, risk management, and resource conservation. The player can also compare their decisions with optimal solutions suggested by the computer model.

7.0 CONCLUSION AND OUTLOOK

In this paper, we have introduced a comprehensive MIP model for planning and executing MEDEVAC missions in military operations. The model incorporates various operational factors, including helicopter capacities, patient triage levels, refueling requirements, and risk assessments associated with different routes. By balancing the dual objectives of maximizing patient care and minimizing mission risk, the model provides a robust framework for optimizing MEDEVAC operations under complex and dynamic conditions.

The implementation of this model using state-of-the-art optimization software demonstrated its practical applicability and potential for real-world scenarios. The results from our test case underscore the model's ability to deliver actionable insights, such as the optimal allocation of helicopters and prioritization of patients based on urgency and resource availability. The efficient computation of solutions, even under tight time constraints, highlights the model's feasibility for operational use. However, when it comes to large instances with many casualties, vehicles, and locations, the runtime for the MIP solver may increase drastically, so that a real-time mission planning is no longer possible. In this case, one has to divert to other optimization methods that do not guarantee to find a global optimum, but are much faster, namely heuristics such as Genetic Algorithms, Simulated Annealing, or Tabu Search.

Beyond the mathematical model, we explored the innovative use of gamification as a training and educational tool. The development of a MEDEVAC CoSim board game aims to bridge the gap between theoretical optimization models and practical decision-making in the field. This game is designed to enhance the tactical and strategic thinking of military personnel, providing a simulated environment where players can experiment with different scenarios and learn from their outcomes. The positive experiences from similar applications in UAV mission planning suggest that this approach could significantly benefit MEDEVAC planners and operators.

Looking forward, there are several avenues for further research and development. One key area is the refinement of the MIP model to include more granular data and real-time updates, potentially integrating with live data feeds from wearable devices and AI forecasting for dynamic mission planning. Additionally, the exploration of heuristic and metaheuristic approaches could further improve the model's computational efficiency, enabling faster decision-making in time-sensitive situations.

The gamification aspect also presents opportunities for enhancement, such as the incorporation of more complex scenarios and the use of digital platforms for broader accessibility. Future work will focus on testing the board game with actual military personnel to validate its effectiveness as a training tool and to gather feedback for iterative improvements.

In conclusion, the integration of advanced optimization techniques and gamification offers a promising pathway to enhance MEDEVAC mission planning and execution. By continuing to develop and refine these tools, we can better prepare military personnel for the challenges they face, ultimately improving outcomes in critical MEDEVAC operations.

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