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Evaluating the Military Medical Evacuation Dispatching and Delivery Problem via Simulation and Self-Exciting Hawkes Process

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EVALUATING THE MILITARY MEDICAL EVACUATION DISPATCHING AND DELIVERY PROBLEM VIA SIMULATION AND SELF-EXCITING HAWKES PROCESS

THESIS

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Abstract

The location, allocation, and utilization of military medical evacuation (MEDEVAC) resources significantly impact the quality and timeliness of medical care to injured troops. In 2009, Secretary of Defense Robert Gates introduced the Golden Hour mandate that entails the evacuation of critically-injured troops to military treatment facilities (MTFs) within an hour to prevent further complications. To develop high-quality policies that improve MEDEVAC system performance, several papers in the current literature assume that MTFs have both the capacity and capability of treating any patient, regardless of the type of injury. However, these assumptions are unrealistic when conducting high-intensity operations. While acknowledging MTF limitations, this thesis simulates the MEDEVAC dispatching and delivery system to evaluate the impact that MTF limitations have on system performance. Furthermore, this thesis adopts a realistic approach to modeling request arrival behavior via a Hawkes process. Results indicate that the MEDEVAC system, under the baseline policy, fails to meet the standard set by the Golden Hour mandate. As such, this thesis explores simple heuristic policies that seek to improve system performance. The insights gained from these explored policies highlight the substantial impact MTFs have on MEDEVAC systems and should be considered in future research.

To my wife, you are simply amazing. I am thankful to share this life with you, and I am excited to see what the Lord has planned for us next. I love you.

"Be strong and courageous. Do not be afraid nor discouraged, for the Lord your God is with you wherever you go." – Joshua 1:9

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Virbon B. Frial

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EVALUATING THE MILITARY MEDICAL EVACUATION DISPATCHING AND DELIVERY PROBLEM VIA SIMULATION AND SELF-EXCITING HAWKES PROCESS

I. Introduction

The United States (U.S.) military continues to use medical evacuation (MEDEVAC) as the primary method to ensure wounded personnel in the battlefield are given proper treatment in a timely manner. MEDEVAC operations entail the sequential planning of fulfilling 9-line MEDEVAC requests (i.e., requests for MEDEVAC support from a combat unit that includes nine standardized components of information), dispatching available medical transport vehicles, and sustaining patients during transport to assigned medical treatment facilities (MTFs). Patient survivability greatly depends on how effectively and efficiently MEDEVAC planners manage their scarce resources to attain desired outcomes for wounded personnel. A well managed MEDEVAC system increases morale and confidence in military personnel, which corresponds to improvements in mission-related duties (Department of the Army, 2019).

Although casualties can be transported aboard non-medical vehicles via a casualty evacuation (CASEVAC) system, this thesis focuses only on the application of a MEDEVAC system. Furthermore, this thesis analyzes only the dispatching of medically-equipped aerial units, particularly helicopters, to service 9-line MEDEVAC requests. This thesis incorporates the use of the Sikorsky HH-60M Black Hawk. The U.S. Army uses the Sikorsky HH-60M Black Hawk, which has a cruise speed of 152 knots and a maximum speed of 191 knots. It can also be modified to carry up to six patients at a time.

An important difference between this thesis and previous MEDEVAC research is the comprehensive use of an MTF. Previous research assumes that casualties are always delivered to the closest MTF, regardless of the MTF's capability. Moreover, the current MEDEVAC literature does not account for MTF capacity and assumes enough beds are available for all incoming patients, regardless of arrival and service rates. These assumptions may be unrealistic, especially during high-intensity operations, and hinder the implementation of developed policies in a real MEDEVAC scenario. To mitigate this issue, this thesis explicitly models the capacity for each MTF.

Moreover, this research considers different triage levels and medical roles, which correspond with the different medical capabilities provided by an MTF and a medical transport unit. Accordingly, MEDEVAC planning needs to account for these factors. If a nearby MTF is unavailable or does not have the capability to treat the patients of a particular request, the patients of that request are either serviced by a capable MTF elsewhere or is rejected by the MEDEVAC system and serviced via CASEVAC.

There are three triage levels: urgent, priority, and routine. An Army MEDEVAC system operates in accordance with the assigned precedence (Department of the Army, 2015). Urgent cases, which are of the highest precedence, refer to patients that require immediate evacuation within an hour to minimize potentially-severe health complications and avoid permanent disability. Priority cases refer to sick and wounded patients that require prompt medical care. These patients must be evacuated within four hours. Routine cases, which are of the lowest precedence, refer to sick and wounded patients whose condition is not expected to decline significantly. These patients must be evacuated within 24 hours. If a patient is rejected by the MEDEVAC system, it is assumed that the patient will be provided medical care via CASEVAC and unit-level medical personnel within the recommended time.

There are four roles of medical care: Role 1, 2, 3, and 4. Role 1 medical care is provided by combat medics during evacuation from the combat zone to the MTF. These combat medics perform immediate life-saving measures and can use blood transfusion kits aboard the transport vehicles. Role 2 medical care is provided by medical professionals assigned to temporary treatment facilities. It is short-term care (i.e., 1 to 3 days) that provides trauma management capabilities greater than what is available at Role 1. Priority MEDEVAC requests can be serviced by Role 2 MTFs or higher. Role 3 medical care is provided by medical professionals assigned to established treatment facilities. Role 3 MTFs are equipped with the necessary supplies and staff to provide care to all levels of injury. Urgent MEDEVAC requests can only be serviced by Role 3 MTFs or higher. Role 4 medical care is provided only in the continental United States treatment facilities. Role 4 is defined by the most advanced medical care and is tailored for patients who need long-term care (Department of the Army, 2015). This thesis incorporates only Roles 1, 2, and 3 medical care. Role 1 medical care is provided by the MEDEVAC unit during evacuation, whereas Roles 2 and 3 are provided by the MTFs. Role 4 medical care involves an out-of-theater patient transport and is out of the scope of this thesis.

Due to the complex nature of a deployed environment, uncertainty significantly affects how MEDEVAC resources are managed. Request arrival rates change with time and depend on past events; a recent event in a particular area increases the likelihood of another event occurring relatively soon after the original event in the same or nearby area. Few studies consider stochastic processes that do not assume independence and utilize a constant rate for event occurrences to evaluate the military MEDEVAC system performance. This thesis leverages self-exciting processes via Hawkes processes to model a more realistic approach with respect to how request arrival rates change over time.

Ultimately, this thesis seeks to evaluate the performance of a notional, synthetically generated MEDEVAC scenario in Bosnia-Herzegovina of the post-Bosnian war based on different dispatch and delivery policies via quantitative performance metrics. A simulation model is constructed to represent the operational dispatch and delivery processes of a MEDEVAC system while considering a more realistic approach to how requests arrive.

The remainder of this thesis is organized as follows: Chapter II provides a review of previous research pertaining to civilian emergency medical service (EMS) response and military MEDEVAC systems. Chapter III presents the MEDEVAC system simulation model and the Hawkes process design. Chapter IV covers an application of the MEDEVAC simulation model based on a representative scenario in Bosnia-Herzegovina and provides results and comparisons of alternative dispatching and delivery policies to improve MEDEVAC system performance. Chapter V concludes the thesis and proposes recommendations for future research.

II. Literature Review

This chapter discusses the current literature on civilian EMS response systems and military MEDEVAC systems. Although civilian EMS response systems and military MEDEVAC systems are similar in structure, they differ in context. Civilian EMS response systems often dispatch ground-based ambulance vehicles, whereas military MEDEVAC systems often dispatch medically-equipped helicopters. Moreover, MEDEVAC operations often change depending on the risk and complexity of the mission. For example, military MEDEVAC scenarios usually involve severely injured personnel and may require the use of armed escorts, depending on threat levels. Hence, policies generated for civilian EMS response systems may differ from policies generated for military MEDEVAC systems. This thesis combines the important aspects of both civilian EMS response and military MEDEVAC literature to build a realistic simulation of a military MEDEVAC system. This chapter also discusses the methods applied to determine and evaluate policies.

History shows that the application of operations research techniques dramatically improves the policies of emergency response systems (Green and Kolesar, 2004). Specific to military MEDEVAC systems, these techniques include math programming (e.g., Bastian (2009), Grannan and McLay (2014), Jenkins et al. (2020)), Markov decision processes (MDP) (e.g., Keneally et al. (2016), Jenkins et al. (2020), Graves et al. (2021)), and approximate dynamic programming (ADP) (e.g. Rettke et al. (2016), Dennie (2021), Jenkins et al. (2021), Wooten (2021)). However, such techniques often fail to fully encompass the dynamics of an emergency system (Yue et al., 2012). Important components are often set aside as assumptions in order to achieve model tractability. However, using simulation modeling, this thesis attempts to integrate factors that were discarded as assumptions in the current MEDEVAC literature to holistically evaluate the performance of a MEDEVAC system.

Pinto et al. (2015) provide a general framework for building simulations that imitate EMS response systems. Their framework focuses on three main areas: call generation, ambulance dispatch, and ambulance journey. Each area has complex processes but contains simple policies applicable to all modeled systems. Additionally, the proposed framework utilizes system performance metrics, such as response time and ambulance utilization, that are deemed important to patients and system planners.

Previous research also discusses the most appropriate metric to evaluate an emergency response system. McLay and Mayorga (2010) state that most civilian EMS systems are evaluated based on response times. This metric, known as response time threshold (RTT), is the time elapsed from when a particular request is submitted to when an ambulance unit arrives on-scene. However, based on the complex nature of a deployed environment, several unknown factors can affect the outcome of a MEDEVAC operation. Furthermore, travel and load times are longer due to the potential threat levels associated with each mission. As a result, the performance of a MEDEVAC system should be assessed by the total patient response time (i.e., time from when requests arrive to when a patient is evacuated to an MTF, and not solely on on-scene arrival times).

Recent research suggests the performance of a MEDEVAC system may not be accurately assessed solely on the RTT metric. Erkut et al. (2008) shows that patient survivability is a more accurate measure, as patient survivability directly reflects patient outcome. In 2009, Secretary of Defense Robert Gates introduced the Golden Hour mandate, which calls for evacuation of urgent patients to MTFs within an hour. An assessment conducted by Kotwal et al. (2016) reveals that fatality rates were reduced by almost fifty percent following the mandate. Accordingly, subsequent civilian EMS response and military MEDEVAC research focuses on patient survivability as

opposed to RTT (e.g., McLay (2011), Bandara et al. (2012), Mayorga et al. (2013), Grannan (2014), Rettke et al. (2016), Jenkins et al. (2020), Robbins et al. (2018), Dennie (2021), Graves et al. (2021), Wooten (2021)).

This thesis applies the framework and performance metrics proposed by Pinto et al. (2015) to create a MEDEVAC simulation model. Additionally, other performance metrics, such as resource utilization and patient survivability according to the Golden Hour mandate, are utilized to evaluate the performance of a MEDEVAC system.

This thesis also incorporates the different factors examined in the current EMS literature. Keneally et al. (2016) examine the dispatch policies used by MEDEVAC systems in a deployed environment. The proposed model incorporates threat conditions in the area of responsibility (AOR) and patient triage levels based on severity of injury. Grannan and McLay (2014) utilize a model that allows for batch arrival of casualties (i.e., a single request is submitted to conduct evacuation for multiple patients) and incorporates distinguishable MTFs. Grannan and McLay (2014) suggest a policy to evacuate urgent and priority patients to more established MTFs, unless extremely distant, and routine patients to nearby MTFs.

Jenkins et al. (2020) contribute to the MEDEVAC literature by using admission control and queuing of requests. A decision is made based on the the system's current state and the request's origin and triage level. When a particular request arrives, the system decides on one of three possible actions: allow the request to enter the system queue, immediately service the request, or reject the request from entering the system. Jenkins et al. (2020) also confirm that flight speed is crucial in improving system performance.

The current EMS response literature explores the comprehensive use of hospitals. Li et al. (2021) explore the issue of ambulance offload delays (AODs). When a nearby

hospital reaches max capacity, ambulance units evacuate patients to either a more distant hospital or wait in the queue at the nearby hospital. As these patients await service by the designated hospital, their assigned ambulance units continue to provide treatment. Issues arise when these ambulance units are temporarily unavailable and cause delays in servicing other requests. Li et al. (2021) reveal that it is beneficial to send patients to more distant hospitals than to wait in a queue at nearby hospitals. However, this policy does not include urgent patients because they are immediately serviced upon arrival. This thesis circumvents AOD issues for a deployed environment by initiating the request queue before MEDEVAC units and MTFs are assigned.

Additionally, Lee and Lee (2018) examine an optimal hospital scheduling policy for a mass casualty incident. The research outlines a scenario in which the assigned hospital expects to reach max capacity. As such, hospital staff must properly allocate resources to maximize the number of lives saved. The model accounts for bed capacity and allows for admission control. Lee and Lee (2018) find a simple rationale behind their optimal policy structure: routine patients are rejected to save current beds for the large number of urgent patients expected to arrive. Otherwise, the optimal policy suggests to treat the current patient, regardless of triage level.

This thesis utilizes a Hawkes Process (Hawkes, 1971) to model a more realistic approach of request arrivals. Egesdal et al. (2010) utilize the Hawkes Process to model gang rivalries that plague the district of Hollenbeck in Los Angeles, California. The Los Angeles Police Department provided data of gang-related crimes that occurred between 1999 and 2002. Upon further analysis, Egesdal et al. (2010) confirm that the occurrence of gang-related crimes are better represented using a Hawkes Process, as opposed to using a memoryless Poisson process. Lewis et al. (2012) examine the temporal occurrences of civilian deaths in Iraq. The research suggests that if nearby events are positively correlated, then these events can be represented by a self-exciting

point process. Lewis et al. (2012) also suggest that the arrival rates of a point process can be split into background and self-exciting components. Background rates function independently, whereas self-exciting rates rely on the intensity of prior events. Lewis et al. (2012) show that models using event-triggered rates outperformed models using constant rates. Additionally, Kroese and Botev (2013) provide a specific example of a collection of points generated by a Hawkes Process. Similar to this thesis, Laub et al. (2015) develop a temporal Hawkes process algorithm to model arrival times. This thesis modifies the algorithm to model the arrival times of MEDEVAC requests.

III. Methodology

This chapter presents the methodology implemented in this thesis. Section 3.1 provides an overview of the sequence of events that follows a request through a military MEDEVAC system. Next, Section 3.2 presents a modified algorithm that generates request arrival times according to Hawkes process. Finally, Section 3.3 presents the model used to simulate the MEDEVAC system.

3.1 MEDEVAC System Sequence of Events

When a 9-line MEDEVAC request is submitted, information is reported to the dispatching authority to ensure proper evacuation of the wounded personnel (i.e., patients) attributed to the request. The request information includes, but is not limited to, the location of the nearest casualty collection point (CCP), the number of patients, and each patient's triage level. After the ground unit submits the request, the ground unit transfers the patients to the reported CCP where the patients await evacuation to an MTF. Although it is not explicitly stated in the request, the request's overall triage level is determined based on the highest triage level of all the patients attributed to the request. Therefore, MEDEVAC planners must adjust operations to ensure the request is properly serviced. Once the patients of the request arrive at the MTF, each patient is treated according to their individual triage level.

Figure 1 depicts the sequence of events that follow the arrival of a request. After a request arrives, the system enters a waiting period wherein the dispatching authority assesses the current resources (i.e., the status of each MEDEVAC unit and the number of available emergency beds at each MTF) available to service the request. If resources are available, the dispatching authority implements a myopic policy wherein the request will be serviced by the nearest MEDEVAC unit and the nearest, capable

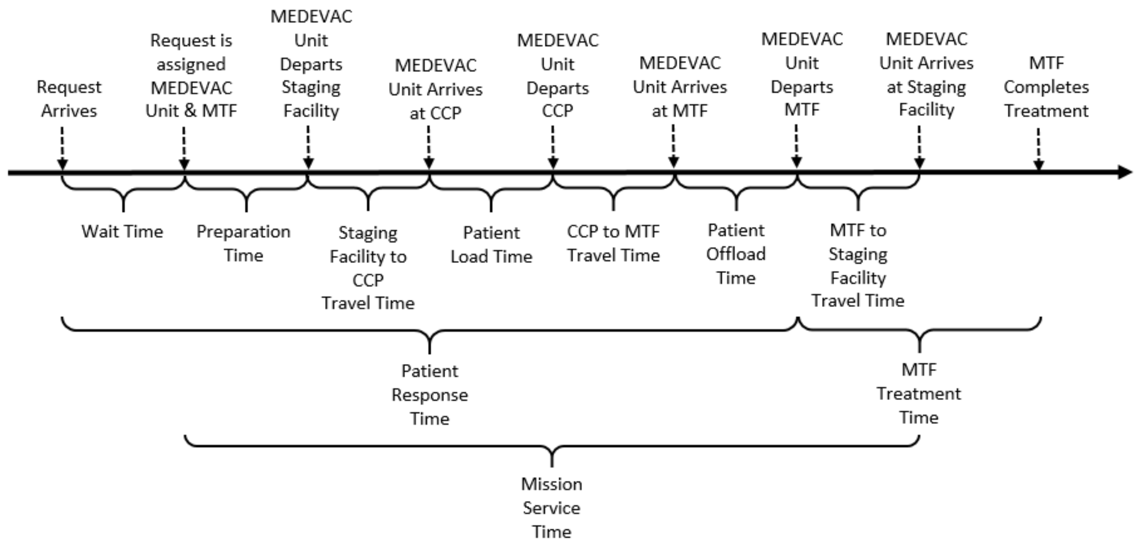

Figure 1. MEDEVAC System Timeline

MTF. The assigned MTF must be able to fully accommodate the request (i.e., the MTF possesses the capability and the amount of available emergency beds necessary to treat all patients attributed to the request). Since MEDEVAC helicopters can carry up to six patients at a time, it is logistically more efficient to conduct a full evacuation wherein all patients attributed to a MEDEVAC request are evacuated simultaneously by the same MEDEVAC unit to the same MTF, as opposed to utilizing different MEDEVAC units and/or MTFs. It is assumed that this practice eases the burden on MEDEVAC personnel.

After a MEDEVAC unit and an MTF are assigned, preparations to dispatch the assigned MEDEVAC unit begin (e.g., pre-mission briefs, preflight inspection, and maintenance). Additionally, the required amount of emergency beds is reserved at the assigned MTF. It is assumed that these emergency beds are prepared and medical staff is available upon arrival of the patients. Once dispatch preparations are complete, the assigned MEDEVAC unit departs its staging facility and travels to the designated CCP. Upon arrival at the CCP, the MEDEVAC unit loads the patients into the aircraft, departs the CCP, and subsequently evacuates the patients to the assigned

MTF. Upon arrival at the MTF, the MEDEVAC unit offloads the patients from the aircraft and formally transfers medical responsibilities to the awaiting medical staff. The MEDEVAC unit then departs the MTF and returns to its staging facility. Concurrently, the medical staff begins treatment to stabilize the patients. After a patient is stabilized, the patient is either discharged from the MTF, or is transferred to the intensive care unit for follow-up treatment. Afterwards, the medical staff disinfects the used bed and replenishes medical supplies for the next patient.

3.2 Hawkes Process

Several papers in the current MEDEVAC literature use a homogeneous Poisson process to model the arrival of 9-line MEDEVAC requests. Utilizing a homogeneous Poisson process requires only a single parameter (i.e., the constant arrival rate λ) to be defined and assumes independence between the arrival behaviors of requests. However, Egesdal et al. (2010) demonstrate that there are certain scenarios better modeled using a non-homogeneous Poisson process. The request arrivals of a MEDEVAC system are better represented using a non-homogeneous Poisson process, such as the Hawkes process. When utilizing a Hawkes process, the arrival rate λ is modified to account for the increased intensity driven by previous requests. Let $t_1, t_2, ..., t_k$ denote the sequence of request arrivals up to time t. The Hawkes conditional intensity is given by

$$\lambda^*(t) = \lambda + \sum_{t_i < t} \mu(t - t_i). \quad (1)$$

Equation 1 requires specifications of an arrival rate λ, which is now referred to as the background arrival rate, and an excitation function $\mu(\cdot)$. A popular choice for the excitation function is one that reflects exponential decay.

$$\lambda^*(t) = \lambda + \sum_{t_i < t} \alpha e^{-\beta(t - t_i)} \tag{2}$$

Hence, Equation 2 is further specified with constants α and β. The overall arrival rate λ^* remains constant at rate λ. A request's arrival into the system increases the overall arrival intensity by factor α. As time elapse, the influence of the request's arrival decreases at decay rate β (Laub et al., 2015).

Following the immigration-birth example described in Laub et al. (2015), knowing the branching ratio is useful in developing simulation algorithms. An individual that enters the system at time t_i produces generations of offspring (i.e., first-generation, second-generation, and so on) at times $t > t_i$ at a rate of $\mu(t - t_i)$. The collection of these generations can be expressed as the descendants of that individual. Accordingly, the branching ratio is the expected number of descendants from that individual. The branching ratio of exponentially decaying intensity is given by $n = \frac{\alpha}{\beta}$.

Using an algorithm presented in Laub et al. (2015), this thesis develops a modified Hawkes Process algorithm that generates a realistic sequence of MEDEVAC request arrival times and records their nearest CCP locations. This thesis assumes that these major incidents occur near any of the possible CCP locations. The modified algorithm is presented in Algorithm 1. Parent requests arrive into the system as a result of major incidents involving enemy engagement, improvised explosive device attacks, and so on. These parent requests follow a homogeneous Poisson process of arrival rate λ. Moreover, the number of parent requests $k \in \mathbb{N}$ is expressed by a Poi(λT) distribution over a time interval $[0, T]$. The number of possible CCP locations is denoted by $L \in \mathbb{N}$, and the CCP location of a parent request i is denoted by $O_i \in \mathbb{N}$, such that $O_i \leq L$. The sets of parent request CCP locations $\{O_1, O_2, ..., O_k\}$ and arrival times $\{C_1, C_2, ..., C_k\}$ are generated as uniformly distributed random numbers over interval $[1, L]$ and the time interval $[0, T]$, respectively.

Algorithm 1 Generate MEDEVAC Request Arrival Times & CCP Locations Using Hawkes Process

```
k ← Poi(λT)
O_1, O_2, ..., O_k ← Unif(1, L)
C_1, C_2, ..., C_k ←(iid) Unif(0, T)
D_1, D_2, ..., D_k ←(iid) Poi(n)
List ← {C_1, C_2, ..., C_k}
for i ← 1 to k do
  if D_i > 0 then
    E_1, E_2, ..., E_{D_i} ←(iid) Exp(β)
    List ← List ∪ {C_i + E_1, C_i + E_2, ..., C_i + E_{D_i}}
  end if
end for
Remove arrival times > T from List
Sort List
```

The arrival of descendent requests succeed the arrival of their parent requests. These descendant requests follow a non-homogeneous Poisson process. The i^{th} parent's descendant arrives with intensity $\mu(t - C_i)$, where $t > C_i$, and the number of descendent requests of the i^{th} parent request $D_i \in \mathbb{N}$ is Poi(n) distributed. Given that there are D_i descendant requests that succeed parent request i, inter-arrival times are generated using an exponential distribution of decay rate β. Therefore, the set of arrival times for the descendent requests of parent request i is $\{C_i + E_1, C_i + E_2, ..., C_i + E_{D_i}\}$. The list of request arrival times over time interval $[0, T]$, as well as their respective CCP locations, is sorted in ascending order by arrival time. The sorted list is then loaded into the simulation model.

3.3 MEDEVAC System Simulation Model

A simulation model is designed to resemble the operational sequence of the military MEDEVAC system, as depicted in Figure 1. Since multiple 9-line MEDEVAC requests can be serviced, the simulation model allows for multiple processes to develop concurrently. Prior to the start of a simulation run, request arrival times are

generated using a modified Hawkes Process algorithm (i.e., Algorithm 1) presented in Section 3.2, and are scheduled as future events in the simulation. As requests arrive, they immediately enter the queue and are serviced according to a First-Come First-Serve (FCFS) scheduling algorithm (i.e., older requests are prioritized as resources become available). When a request is assigned to a MEDEVAC unit and MTF, the simulation model adheres to the myopic policy. The time at which the simulation run terminates is specified by the model user.

The state of the system, at any point during a simulation run, is described by the number of requests in the queue, the status of each MEDEVAC unit (i.e., a MEDEVAC unit is either idle or servicing a request), and the number of used beds at each MTF's emergency department. Furthermore, the state of the system transitions to a new state when one of four events occur: 1) a request arrives, 2) a MEDEVAC unit and MTF are assigned to a request, 3) a MEDEVAC unit returns to its staging facility, or 4) an MTF completes a patient treatment. Once an event occurs, its event process initiates immediately in the simulation. Additionally, the system records the time of when the event occurs. Events that are scheduled to occur after the simulation terminates is not recorded. Operation processes cease when the simulation reaches it termination point. Otherwise, the simulation continues.

At the start of a simulation run, the MEDEVAC system begins at an empty state (i.e., no requests in queue, all MEDEVAC units are idle, and all emergency beds are available at each MTF). At some future time, a 9-line MEDEVAC request arrives into the system, and Event Process 1, which is depicted in Figure 2, initiates. When a request arrives into the system, the system's current state transitions to a new state wherein the length of the request queue increases by one. The system then observes the time of when the request arrives to determine if the simulation run terminates. If the simulation run continues, the arriving request is placed at the end of the queue so

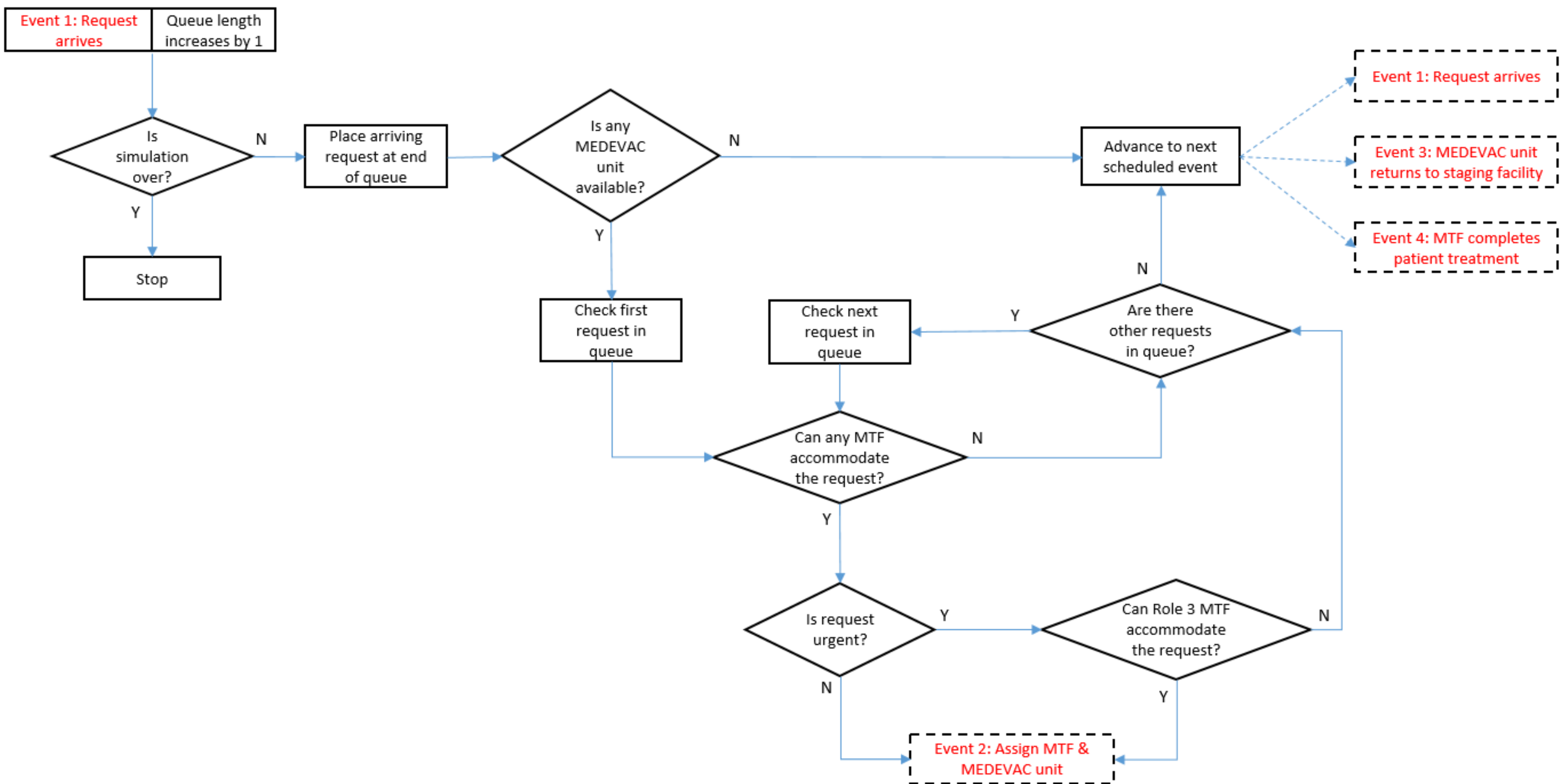

Figure 2. Event Process 1: Request arrives

that the system adheres to the FCFS scheduling algorithm. Next, the system checks if any MEDEVAC units are available. If none of the MEDEVAC units are available, then Event Process 1 ends and the simulation proceeds to the next scheduled event. If a MEDEVAC unit is available, then the system examines the request queue and screens the first, and oldest, request. If no other requests are in queue, then the system screens only the arriving request. Afterwards, the system checks if an MTF has available emergency beds to treat all the patients attributed to the request. If an MTF can accommodate the request, the system reexamines the request's triage level. If the request is non-urgent, then Event Process 2 is initiated wherein a MEDEVAC unit and MTF is assigned to the request. Event Process 2 is depicted in Figure 3. If the request is urgent, then the system also checks if the Role 3 MTF can accommodate the request. If so, then Event Process 2 is initiated. If not, then the system reexamines the queue and screens the next oldest request. The system will continue to screen other requests in queue until a request is accommodated, or until all requests in queue have been screened. If all MEDEVAC units are unavailable or all requests in queue have been screened, then Event Process 1 ends and the simulation proceeds to the next scheduled event.

Prior to initiating Event Process 2, a condition holds such that the request can be serviced by a MEDEVAC unit and accommodated by an MTF. When Event Process 2 initiates, the system's current state transitions to a new state by adhering to the myopic policy. During the state transition, the assigned MTF's number of used emergency beds increases by the number of patients attributed to the request, and the assigned MEDEVAC unit is no longer idle. Additionally, the request is removed from the queue. Hence, the queue length decreases by one. Next, the system generates the MEDEVAC unit preparation time according to a normal distribution similar to one presented in Bastian (2010). Afterward, the system simulates the

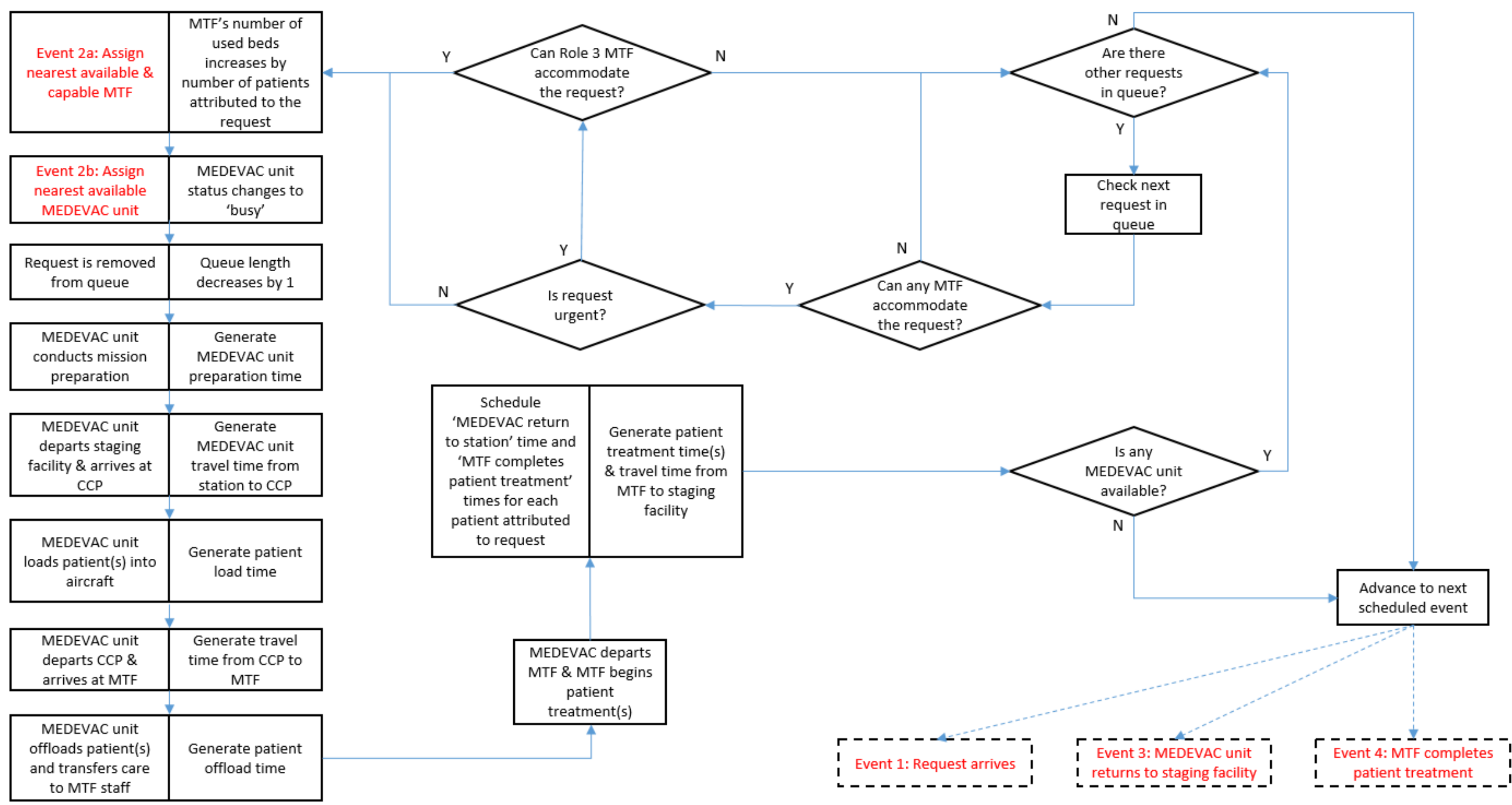

Figure 3. Event Process 2: Assign MEDEVAC Unit & MTF

MEDEVAC unit preparing for the mission, traveling from the staging facility to the request's CCP, loading the patients into the aircraft, and then traveling from the request's CCP to the assigned MTF. Loading and travel times are generated according to a triangular distribution. The travel time mode parameter is calculated by dividing the euclidean distance between the origin and destination points by the assigned MEDEVAC aircraft's cruise speed, and is adjusted based on the earth's curvature. Next, the system simulates the MEDEVAC unit offloading the patients and transferring patient care to the MTF's medical staff. Similar to the system presented in Bastian (2010), patient offload time is generated according to a normal distribution. Finally, once patient care is transferred, the system simulates the MEDEVAC unit departing the MTF, and concurrently, the MTF's medical staff initiating patient treatment. The MEDEVAC unit's travel time from the MTF to the staging facility and each patient's treatment time are generated according to a triangular distribution. The times at which a MEDEVAC unit returns to its staging facility or an MTF completes patient treatment are scheduled as future events in the simulation.

Before Process Event 2 ends, the system reassesses its current resources. If a MEDEVAC unit is available, then the system examines the request queue and screens for a request that can be accommodated by an MTF. If a request can be accommodated, then the simulation repeats Event Process 2 for that request. If none of the MEDEVAC units are available, the request queue is empty, or all requests in queue have been screened, then Event Process 2 ends, and the simulation proceeds to the next scheduled event.

Once a MEDEVAC unit returns to its staging facility, Event Process 3 initiates, and the system's current state transitions to a new state. Event Process 3 is depicted in Figure 4. During the state transition, the MEDEVAC unit returns to idle and is available to service another request. Additionally, the system observes the time of

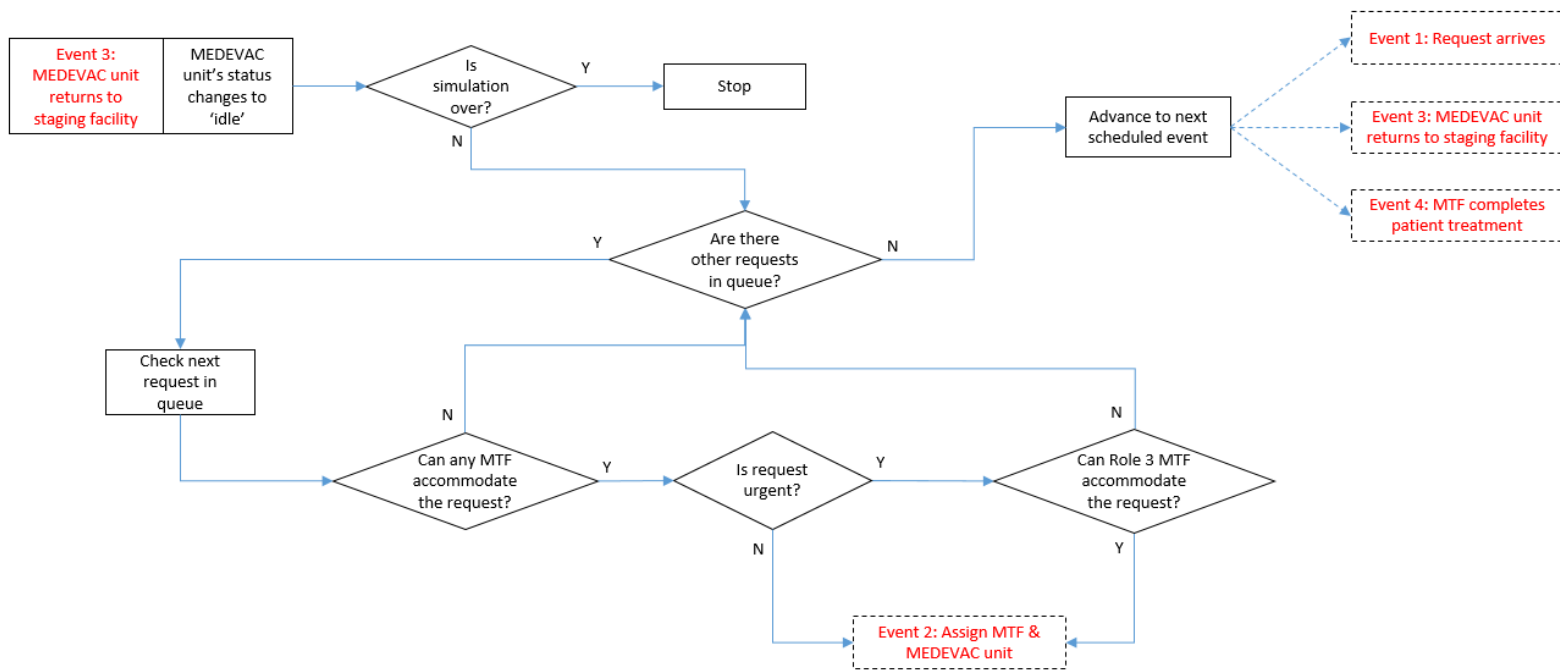

Figure 4. Event Process 3: MEDEVAC unit returns to staging facility

when the MEDEVAC unit returns to the staging facility to determine if the simulation run terminates. If the simulation run continues, the system examines the request queue based on the FCFS scheduling algorithm and screens for a request that can be accommodated by an MTF. If a request can be accommodated, then the simulation proceeds to Event Process 2. If the request queue is empty or all requests in queue have been screened, then Event Process 3 ends, and the simulation proceeds to the next scheduled event.

Once an MTF completes a patient treatment, Event Process 4 initiates and the system's current state transitions to a new state. Event Process 4 is depicted in Figure 5. During the state transition, the MTF's number of used emergency beds decreases by one. The simulation, however, does not explicitly model the events that pertain to the patient, after they have been stabilized. The system then observes the time of when the MTF completes the patient treatment to determine if the simulation run terminates. If the simulation run continues, the system assesses its current resources. If a MEDEVAC unit is available, then the system examines the request queue based on the FCFS scheduling algorithm and screens for a request that can be accommodated by an MTF. If a request can be accommodated, then the simulation proceeds to Event Process 2. If none of the MEDEVAC units are available, the request queue is empty, or all requests in queue have been screened, then Event Process 4 ends, and the simulation proceeds to the next scheduled event.

As mentioned in Chapter I, the performance of the MEDEVAC system is evaluated using several quantitative performance metrics. To evaluate the performance of each MEDEVAC unit, average utilization rate (i.e., percentage of time a MEDEVAC unit is busy) and average mission time (i.e., amount of time that elapsed from when a MEDEVAC unit is assigned to a request to when the MEDEVAC unit completes the mission and returns to the staging facility) are recorded. To evaluate the performance

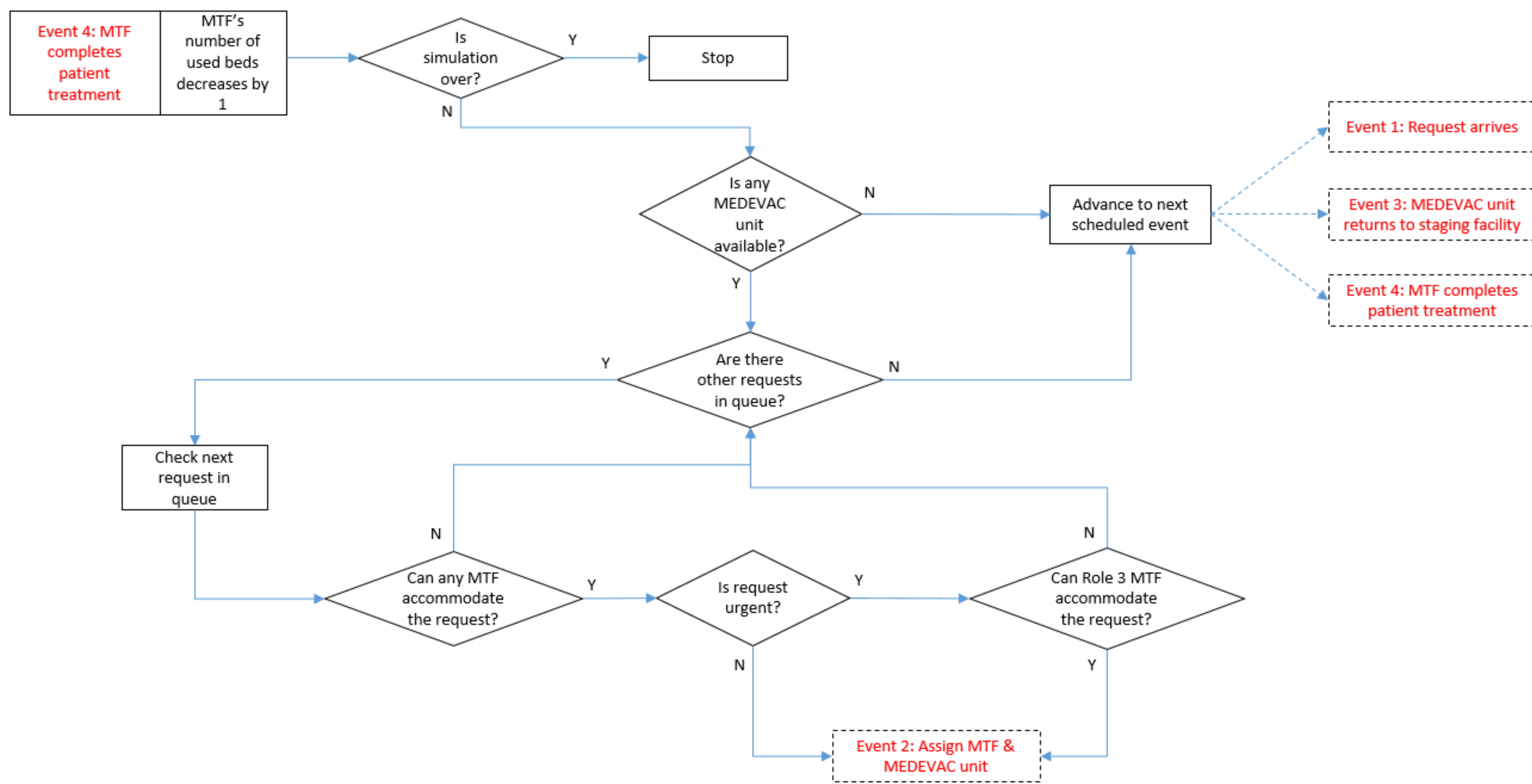

Figure 5. Event Process 4: MTF completes patient treatment

of each MTF, the average number of beds used is recorded. Additionally, the average and maximum attributes of both patient response and wait times are recorded for each triage level. Other performance metrics such as Golden Hour rate (i.e., percentage of urgent patients whose response time is within one hour), average queue length, and maximum queue length are also recorded.

To improve estimation of the performance metrics, the simulation is replicated 30 times. Using a sample size greater than 25 is sufficient so that the Central Limit theorem holds (Hogg et al., 2015). The Central Limit theorem states that a distribution of samples approximates to a normal distribution when the sample size is sufficiently large, regardless of the sample's true distribution. Thus, an acceptable 95% confidence region for each performance metric can be calculated. Furthermore, the simulation utilizes common random numbers to ensure reproducibility, which is particularly useful when evaluating how a MEDEVAC system performs using different dispatching and delivery policies.

IV. Testing, Results, and Analysis

This chapter expands on the representative military MEDEVAC scenario examined, as well as the analysis and results of this thesis. This chapter is divided into five sections. Section 4.1 describes the examined representative military MEDEVAC scenario, relevant factors, and baseline policy. Section 4.2 presents the performance results of the MEDEVAC system when the baseline policy is implemented. Section 4.3 explores alternative policies to improve the baseline results. Section 4.4 provides a comparison of all explores policies. Finally, Section 4.5 conducts sensitivity analyses to evaluate robustness of the best explored policies.

4.1 Representative Scenario & Baseline Policy

Bosnia-Herzegovina's separation from Yugoslavia resulted in a violent civil war that lasted from April 1992 to November 1995. In late 1995, a peace agreement, known as the Dayton Peace Accords, ended the civil war. This allowed North Atlantic Treaty Organization (NATO) forces, which included U.S. forces, to enter the country and engage in peacekeeping operations. To facilitate compliance with the Dayton Peace Accords, NATO divided its Implementation Force (IFOR) into three subordinate commands, each of which were assigned to one of the three regions: Multinational Division - North, Multinational Division - Southwest, and Multinational Division - Southeast (Phillips, 2005).

This thesis examines a notional military MEDEVAC planning scenario of the peacekeeping operations in the post-Bosnian war in a 72-hour period. Specifically, this thesis focuses on the U.S.-controlled Multinational Division - North region. In this scenario, there are two coalition bases (i.e., established bases containing a MEDEVAC helicopter landing zone (HLZ) and an MTF) located in Tuzla and Bijeljina. The

coalition base in Tuzla contains a Role 3 MTF, whereas the coalition base in Bijeljina contains a Role 2 MTF. There are also two MEDEVAC stations (i.e., temporary bases that contain an HLZ only) located in Brcko and Doboj. Each of the four locations is allocated one MEDEVAC unit. MEDEVAC Units 1 through 4 are located in Tuzla, Bijeljina, Brcko, and Doboj, respectively. CCPs are selected based on recounted events by Phillips (2005) of locations that experienced casualties during and after the Bosnian War. Figure 6 depicts the placement of the coalition bases, MEDEVAC stations, and CCPs used to generate data for the simulation model.

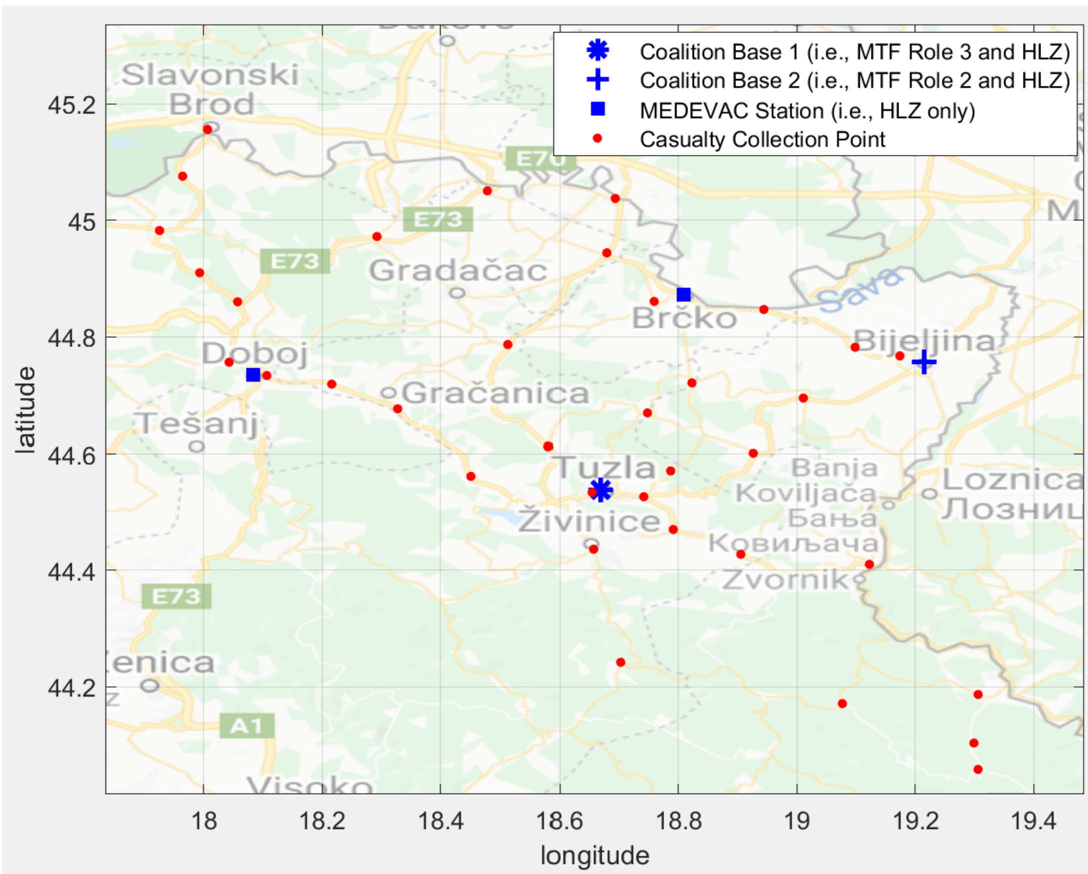

Figure 6. Representative Scenario

A modified Hawkes process algorithm, similar to one presented in Laub et al. (2015), is utilized to model the locations and arrival times of 9-line MEDEVAC requests. Furthermore, appropriate Hawkes process parameters are selected to provide

a sufficient amount of stress on the MTFs in order to evaluate their impact on the MEDEVAC system performance. After initial testing with the Hawkes process parameters, the selected parameters are: background arrival rate of $\lambda = 1$ (i.e., a request is expected to arrive every hour), which is similar to the background arrival rate chosen in Graves et al. (2021), an intensity factor of $\alpha = 1$, and a decay rate of $\beta = 0.75$. Additionally, this thesis assumes triage-level probabilities that are reasonable for this scenario and follow a simple structure. The probability of the system receiving a patient of a specific triage level is half as likely as receiving a patient whose triage level is of the next lower precedence. Hence, the triage-level probabilities are $\frac{1}{7}$, $\frac{2}{7}$, and $\frac{4}{7}$ for urgent, priority, and routine patients, respectively.

Treatment times are estimated using a triangular distribution. Also, this thesis assumes that treatment times are longer for patients with higher triage levels. Appropriate treatment time parameters were selected for each triage level based on discussions with a technician that has several years of EMS experience. Treatment times for urgent patients are estimated at a minimum time of two hours, an average time of three hours, and a maximum time of five hours. Treatment times for priority patients are estimated at a minimum time of 30 minutes, an average time of one hour, and a maximum time of 1.5 hours. Treatment times for routine patients are estimated at a minimum time of ten minutes, an average time of 30 minutes, and a maximum time of 45 minutes. This thesis also assumes that treatment time depends only on a patient's triage level, and not on other factors, such as the number of patients treated at one time.

MEDEVAC unit travel times are also estimated using a triangular distribution. The travel time minimum and maximum parameters are equal to the travel time mode parameter ± 5 minutes. Additionally, for the baseline scenario, HH-60G Black Hawks, which have a cruise speed of 152 knots, are utilized.

This thesis also utilizes several other MEDEVAC operational times based on information presented in Bastian (2010). Mission preparation time is estimated using a normal distribution with a mean time of 20 minutes and a standard deviation of five minutes. Patient load time is estimated using a triangular distribution with a minimum of five minutes, an average of ten minutes, and a maximum of 15 minutes. Patient off-load time at the MTF is estimated using a truncated normal distribution (i.e., only positive values are valid) with a mean of five minutes and standard deviation of two minutes. It is assumed that patient load and offload times do not depend on the number of evacuated patients attributed to the request.

According to Buckenmaier and Mahoney (2015), HH-60M Black Hawk helicopters can be modified to carry up to six litters. For this reason, the simulation model allows a 9-line MEDEVAC request to reference up to six patients. This thesis assumes probabilities for multiple patients of a single request that are reasonable for this scenario and follow a simple structure. The probability of a request arriving with a particular number of patients is twice as likely as a request arriving with the next higher number of patients. Hence, the selected probabilities are $\frac{32}{63}$, $\frac{16}{63}$, $\frac{8}{63}$, $\frac{4}{63}$, $\frac{2}{63}$, and $\frac{1}{63}$, for up to six patients, respectively. This thesis also assumes a maximum capacity of ten beds in each MTF's emergency department. Once a patient is stabilized, the patient is either discharged from the MTF or is transferred to the intensive care unit for follow-up treatment. The used emergency bed then becomes available for the next patient.

The baseline policy follows the MEDEVAC process described in the simulation model of Section 3.3. The baseline policy implements a strict FCFS scheduling algorithm, regardless of the requests' triage levels. Based on a simple myopic policy, the nearest available MEDEVAC unit and capable MTF are assigned to a request. Furthermore, the assigned MEDEVAC unit must conduct a full evacuation service of

the request, if possible. Otherwise, the request stays in queue until it can be fully accommodated. To prevent delays in operations, the system screens other requests in queue to determine if any requests can be accommodated by the current available resources.

4.2 Baseline Policy Results

Utilizing the baseline policy, the MEDEVAC scenario is simulated over a 72-hour period. The simulation is replicated 30 times to generate an acceptable 95% confidence region for each of the performance metrics presented in Chapter III. The baseline results are presented in Table 1.

Based on the performance results in Table 1, MEDEVAC Units 1, 3, 4, and 2 are identified from most to least utilized, respectively. Based on each MEDEVAC unit's location relative to the possible CCPs in the scenario, it can be inferred that the centrally-located MEDEVAC units are utilized more than the outermost-located MEDEVAC units. Conversely, it appears that the missions of the outermost-located MEDEVAC units take significantly longer than missions of the centrally-located MEDEVAC units. With exception to MEDEVAC Units 2 and 3, there are no significant gaps between longest mission times amongst MEDEVAC units.

Results show that the average response time for urgent patients are significantly longer than the average response time for priority and routine patients. Results also reveal that the MEDEVAC system, when implementing the baseline policy, fails to meet the standards determined by the Golden Hour mandate with an average patient response time of 1.67 hours and a Golden Hour rate of 42% for urgent patients. Further investigation shows that there are occurrences in which urgent patients experience maximum response times of 7.85 hours. Allowing these particular incidents to transpire is unacceptable and may result in severe repercussions.

Table 1. Baseline Policy Results

Performance Metric	Mean ± Half-Width
MEDEVAC Utilization Rate (%)	
Unit 1	56.895 ± 2.597
Unit 2	46.141 ± 2.571
Unit 3	52.451 ± 2.345
Unit 4	48.235 ± 2.673
Average MEDEVAC Mission Time (Hours)	
Unit 1	0.873 ± 0.009
Unit 2	0.949 ± 0.013
Unit 3	0.902 ± 0.012
Unit 4	0.940 ± 0.011
Golden Hour Rate (%)	42.092 ± 3.812
Average Patient Response Time (Hours)	
Urgent	1.673 ± 0.123
Priority	1.412 ± 0.087
Routine	1.377 ± 0.078
Max Patient Response Time (Hours)	
Urgent	7.848 ± 1.445
Priority	7.276 ± 1.412
Routine	7.848 ± 1.445
Average Wait Time (Hours)	
Urgent	0.800 ± 0.124
Priority	0.511 ± 0.085
Routine	0.474 ± 0.077
Max Wait Time (Hours)	
Urgent	6.999 ± 1.452
Priority	6.415 ± 1.423
Routine	6.993 ± 1.454
Average Queue Length	0.814 ± 0.147
Max Queue Length	8.400 ± 1.041
Average Beds Used	
MTF 1	6.065 ± 0.251
MTF 2	2.234 ± 0.182

Results show an average queue length of 0.81 requests with a maximum queue length of 8.40 requests. Although the system can reach a relatively high queue length, the low average queue length may indicate that the MEDEVAC system operates with a low queue length for the majority of the simulation run. Also, average wait times for urgent patients are significantly higher than non-urgent patients. Although the average wait time for urgent patients still fall within the guidelines of the Golden Hour mandate, it provides less latitude for MEDEVAC units to operate within the remaining time.

Results also show that MTF 1, which is the only MTF equipped with Role 3 capabilities in this scenario, is utilized significantly higher than MTF 2. This is expected as urgent patients can only be treated at the Role 3 MTF. Further investigation shows a difference in the amount of beds used at each MTF. For example, 6.1 beds, on average, are used at the Role 3 MTF 1, whereas 2.2 beds, on average, are used at the Role 2 MTF 2. Ultimately, MTF 2 is underutilized and places an unnecessary burden on the MTF 1's medical staff.

4.3 Heuristic Policies - Overview

As this thesis explores alternative policies to the problems identified in the previous section, there are a few factors to consider. First and foremost, policies should seek to gain significant improvements in response times for urgent patients. According to the Golden Hour mandate, the MEDEVAC system must perform to this standard such that urgent patients are evacuated to an MTF within an hour. Second, policies must consider ease of implementation for MEDEVAC personnel. Several MEDEVAC papers provide noteworthy results, but the recommended policies may be too complex for MEDEVAC personnel to implement, especially in high-tempo operations. As such, it is recommended that policies should have a structure that is easily recognized.

Third, policies should consider the MEDEVAC personnel workload. Workloads should be relatively manageable, if possible. Finally, it is a MEDEVAC system's moral obligation to service as many requests as possible (Kotwal et al., 2016). Knowing that a MEDEVAC system can perform well under any circumstance provides confidence in military personnel to perform their duties. However, it is possible to encounter situations where it is not feasible for any MEDEVAC system to perform well, even in an optimal manner. Therefore, this thesis also explores admission control features that reject only routine patients. It is assumed that, if rejected, routine patients are able to receive medical care within 24 hours via CASEVAC. Table 2 presents a list of the explored policies and their descriptions. The MEDEVAC system performance results when implementing each of the alternative heuristic policies are compared to the baseline performance results.

4.3.1 Heuristic 1 Policy - Prioritized FCFS Scheduling

Policies should prioritize medical care in terms of triage level. This thesis explores a Heuristic 1 policy that utilizes a prioritized FCFS scheduling algorithm and can be easily implemented. The MEDEVAC system sorts an arriving request in the queue such that older and higher triage-level requests are serviced first. However, the system continues to follow the baseline policy wherein a request can only be serviced based on current available resources. If a request cannot be serviced, then the system screens other requests in queue that can be serviced to prevent delays in operations. The performance results based on the implementation of the Heuristic 1 policy are presented in the second column of Table 3.

When the Heuristic 1 policy is implemented, results show an improvement in patient response times and average wait time for non-routine patients. Additionally, results show a slight increase in the average number of used beds at MTF 2. This may

Table 2. MEDEVAC System Policy Description

Policy	Description
Baseline	MEDEVAC system follows a strict FCFS scheduling algorithm regardless of triage level precedence, assigns nearest and available MEDEVAC unit and capable MTF, and MEDEVAC unit conducts only a full evacuation for patients of a request.
Heuristic 1	MEDEVAC system modifies baseline policy by following a FCFS scheduling algorithm that prioritizes requests according to triage level and time of arrival.
Heuristic 2	MEDEVAC system modifies baseline policy by sending all non-urgent requests to MTF 2. MTF 1 is reserved for only urgent requests.
Heuristic 3	MEDEVAC system modifies baseline policy by allowing a partial evacuation (i.e., service only non-routine patients of a request), if a full evacuation is not feasible, for all requests in queue.
Heuristic 4	MEDEVAC system modifies baseline policy by suspending all non-urgent request operations until all urgent requests in queue have been serviced.
Heuristic 5	MEDEVAC system adds to baseline policy by rejecting all routine requests.
Heuristic 6	MEDEVAC system implements policy that combines Heuristics 1-4.
Heuristic 7	MEDEVAC system implements policy that combines Heuristics 1-5.

Table 3. Heuristic Policy Results

Performance Metric	Heuristic 1	Heuristic 2	Heuristic 3	Heuristic 4	Heuristic 5	Heuristic 6	Heuristic 7
MEDEVAC Utilization Rate (%)							
Unit 1	56.952 ± 2.602	59.306 ± 2.538	56.899 ± 2.516	56.018 ± 2.606	36.316 ± 2.089	59.161 ± 2.618	37.207 ± 2.170
Unit 2	46.392 ± 2.673	48.370 ± 2.837	46.379 ± 2.501	46.796 ± 2.610	23.498 ± 2.198	48.979 ± 2.745	25.501 ± 1.928
Unit 3	52.024 ± 2.091	55.101 ± 2.339	52.388 ± 2.427	51.983 ± 2.410	30.369 ± 1.906	55.282 ± 2.253	31.688 ± 2.001
Unit 4	48.507 ± 2.883	50.566 ± 2.892	48.155 ± 2.748	48.392 ± 2.575	28.867 ± 1.941	50.312 ± 2.782	29.790 ± 1.934
Average MEDEVAC Mission Time (Hours)							
Unit 1	0.875 ± 0.009	0.924 ± 0.010	0.874 ± 0.009	0.870 ± 0.010	0.848 ± 0.012	0.929 ± 0.008	0.887 ± 0.013
Unit 2	0.948 ± 0.014	0.976 ± 0.017	0.949 ± 0.011	0.953 ± 0.012	0.910 ± 0.014	0.978 ± 0.017	0.939 ± 0.018
Unit 3	0.901 ± 0.012	0.941 ± 0.012	0.901 ± 0.015	0.905 ± 0.013	0.881 ± 0.013	0.940 ± 0.011	0.919 ± 0.014
Unit 4	0.939 ± 0.011	0.995 ± 0.009	0.938 ± 0.012	0.944 ± 0.011	0.925 ± 0.011	0.995 ± 0.009	0.969 ± 0.011
Golden Hour Rate (%)	44.956 ± 3.564	50.970 ± 4.015	46.513 ± 3.279	40.691 ± 4.487	56.873 ± 3.001	59.620 ± 3.239	73.078 ± 2.619
Average Patient Response Time (Hours)							
Urgent	1.541 ± 0.113	1.233 ± 0.063	1.449 ± 0.099	1.299 ± 0.086	1.298 ± 0.097	0.999 ± 0.032	0.914 ± 0.032
Priority	1.295 ± 0.064	1.492 ± 0.105	1.310 ± 0.067	1.728 ± 0.173	1.085 ± 0.050	1.285 ± 0.084	1.030 ± 0.060
Routine	1.404 ± 0.087	1.478 ± 0.090	1.231 ± 0.063	1.706 ± 0.170	1.240 ± 0.099	1.527 ± 0.125	1.017 ± 0.055
Max Patient Response Time (Hours)							
Urgent	6.960 ± 1.193	3.629 ± 0.505	5.367 ± 0.979	3.141 ± 0.384	5.324 ± 1.122	1.926 ± 0.233	1.766 ± 0.248
Priority	6.432 ± 1.206	5.618 ± 0.959	5.186 ± 0.988	5.580 ± 0.847	5.000 ± 1.063	4.017 ± 0.660	2.412 ± 0.404
Routine	7.043 ± 1.166	5.981 ± 0.942	5.062 ± 0.991	5.811 ± 0.871	5.327 ± 1.121	5.581 ± 0.902	1.903 ± 0.363
Average Wait Time (Hours)							
Urgent	0.666 ± 0.113	0.359 ± 0.063	0.574 ± 0.099	0.444 ± 0.088	0.450 ± 0.098	0.119 ± 0.031	0.056 ± 0.032
Priority	0.397 ± 0.062	0.556 ± 0.106	0.411 ± 0.066	0.827 ± 0.174	0.216 ± 0.047	0.347 ± 0.087	0.115 ± 0.062
Routine	0.500 ± 0.085	0.537 ± 0.089	0.328 ± 0.059	0.800 ± 0.171	0.367 ± 0.103	0.569 ± 0.120	0.089 ± 0.060
Max Wait Time (Hours)							
Urgent	6.083 ± 1.206	2.781 ± 0.495	4.456 ± 0.994	2.314 ± 0.385	4.518 ± 1.140	0.931 ± 0.252	0.757 ± 0.278
Priority	5.563 ± 1.210	4.663 ± 0.955	4.262 ± 1.005	4.618 ± 0.843	4.224 ± 1.077	2.988 ± 0.666	1.429 ± 0.401
Routine	6.180 ± 1.175	5.031 ± 0.944	4.100 ± 1.015	4.839 ± 0.872	4.513 ± 1.142	4.590 ± 0.928	0.863 ± 0.419
Average Queue Length	0.802 ± 0.151	0.904 ± 0.171	0.704 ± 0.132	1.701 ± 0.420	0.391 ± 0.047	0.881 ± 0.183	0.274 ± 0.060
Max Queue Length	8.467 ± 1.037	8.833 ± 1.055	8.333 ± 1.035	13.433 ± 1.893	4.067 ± 0.609	9.667 ± 1.356	4.200 ± 1.010
Average Beds Used							
MTF 1	6.044 ± 0.249	3.621 ± 0.230	5.913 ± 0.240	5.993 ± 0.250	5.196 ± 0.236	2.991 ± 0.196	2.975 ± 0.195
MTF 2	2.258 ± 0.182	4.838 ± 0.261	2.160 ± 0.164	2.293 ± 0.170	1.281 ± 0.152	4.599 ± 0.237	2.839 ± 0.160

indicate that non-urgent requests that were initially evacuated to MTF 1 when the baseline policy is implemented are now being evacuated to MTF 2 when implementing the Heuristic 1 policy. However, results reveal that changes in any of the performance metrics are not significant. Although the Heuristic 1 policy can be easily implemented and appropriately prioritizes requests according to triage level, it does not provide any notable improvement in MEDEVAC system performance when compared to the baseline policy.

4.3.2 Heuristic 2 Policy - Assign Non-Urgent Requests to Role 2 MTF

Based on the triage level probabilities given in Section 4.1, it is expected that a majority of requests that arrive into the system are routine requests. Furthermore, when implementing a myopic policy, a majority of requests are likely sent to the nearby and centrally-located MTF 1, as opposed to the distant MTF 2. This results in a significant gap in the average number of beds used between the MTFs. Moreover, urgent patients can only be treated by MTF 1, which is equipped with Role 3 capabilities. When there is a shortage of emergency beds at MTF 1 as a result of accommodating non-urgent requests, it impedes how quickly the MEDEVAC system can respond to urgent requests. As such, this thesis explores a Heuristic 2 policy that focuses on re-balancing workloads between each MTF. When the Heuristic 2 policy is implemented, non-urgent requests, which do not require Role 3 medical care, are sent to MTF 2. Essentially, MTF 1 is reserved for urgent requests. However, it is still possible that non-urgent patients are attributed to urgent requests. The MEDEVAC unit will continue to service all patients attributed to the urgent request to prevent logistic burden on the MEDEVAC system. However, time of service remains dependent on current available resources. The performance results based on the implementation of the Heuristic 2 policy are presented in the third column of Table 3.

When compared to the baseline policy results, there are notable improvements in the Golden Hour rate, patient response times, and wait times for urgent patients. Additionally, there is a significant shift between the average number of beds used at MTF 1 and MTF 2, resulting in MTF 2 being utilized more than MTF 1. However, neither MTFs are utilized at a rate nearly as high as MTF 1 was utilized under the baseline policy.

Results also show significant increases in average mission times for MEDEVAC Units 1, 3, and 4. The significant increase in mission times is skewed by the lengthy missions that require evacuation of non-urgent requests to MTF 2 rather than to the nearest MTF. This is further evidenced by the fact that the average mission time for MEDEVAC Unit 2, which is co-located with MTF 2, shows no significant change. The Heuristic 2 policy enables MEDEVAC Unit 2 to operate similarly to how it operated under the baseline policy.

Overall, results suggest that the implementation of the Heuristic policy 2 is advantageous to improving the MEDEVAC system performance. All metrics relating to urgent patients show considerable improvements. Additionally, workloads between the MTFs are re-balanced, and thus, enable MTF 1 to focus on urgent requests. The drawback is that the average MEDEVAC mission times have greatly increased. However, an argument can be made that the increase in average MEDEVAC mission time is not practically significant. MEDEVAC units will continue to operate without noticeable difference in effort.

4.3.3 Heuristic 3 Policy - Partial Request Evacuation

The lack of available emergency beds to conduct a full evacuation causes delays in servicing requests in queue. Urgent requests, in particular, can only be accommodated by MTF 1, which increases the likelihood of delays for servicing urgent requests in

queue. As such, this thesis explores a Heuristic 3 policy that permits MEDEVAC units to conduct a partial evacuation (i.e., evacuate only non-routine patients of a request, if none of the requests in queue can be fully accommodated by an MTF). It is important to note that the Heuristic 3 policy avoids rejection of priority patients as it is assumed that their condition may decline significantly and would require immediate evacuation. Additionally, the Heuristic 3 policy does not affect how routine requests are serviced. A routine request stays in queue until it can be fully accommodated. The performance results based on the implementation of the Heuristic 3 policy are presented in the fourth column of Table 3.

Results show that patient response and wait times have improved significantly for urgent and routine patients. However, results show no notable changes in average utilization rates for the MEDEVAC units, average number of used beds at each MTF, Golden Hour rate, and queue length. It is assumed that it is logistically more efficient for MEDEVAC systems to conduct a full evacuation of a request, but this practice may have a negative impact on how quickly patients are serviced, if a request cannot be fully accommodated. However, further investigation shows that only 4.14% of requests result in partial evacuation. This suggests, at least for this scenario, only a small portion of requests are negatively impacted by a simultaneous evacuation, and is not as much of a concern as initially thought.

4.3.4 Heuristic 4 Policy - Immediate Urgent Patient Service

As mentioned in Section 4.3, the MEDEVAC system should focus efforts on reducing urgent patient response times. As directed by the Golden Hour mandate, reducing the amount of urgent patients whose response time exceed an hour is of the utmost priority. As such, this thesis explores a Heuristic 4 policy that imposes a restriction on servicing non-urgent requests until all urgent requests in queue are serviced. It is ex-

pected that service times for non-urgent patients will increase significantly. However, based on the extent of their injury, non-urgent patients can tolerate longer service times without risking further complication, whereas urgent patients cannot. Thus, it is possible that a MEDEVAC system can operate effectively by prolonging wait times for non-urgent patients in order to service urgent patients quicker. The performance results based on the implementation of the Heuristic 4 policy is presented in the fifth column of Table 3.

As expected, there is a significant improvement in patient response and wait times, but there is a significant increase in non-urgent patient response and queue length. Despite improved service performance for urgent patients, there is no notable improvement in the Golden Hour rate. This may be a result of the average response time for urgent patients that remains longer than an hour. Hence, the percentage of urgent patients that satisfy the Golden Hour criteria has not changed. Additionally, because the Heuristic 4 policy does not prevent non-urgent requests from being sent to MTF 1, it is possible that MTF 1 sees shortages in emergency beds before new urgent requests arrive, thereby showing no improvement in response times for the same urgent patients affected under the baseline policy.

4.3.5 Heuristic 5 Policy - Reject All Routine Requests

A MEDEVAC system may face situations where its personnel cannot keep pace with the amount of requests arriving into the system. As a result, the system is forced to take a selective approach when determining which requests can be serviced. Thus, this thesis explores a Heuristic 5 policy that permits the MEDEVAC system to reject all routine requests that arrive into the system. The policy, however, does not reject routine patients of non-routine requests. The MEDEVAC system will continue to service these routine patients simultaneously with the non-routine patients of the

same request. The performance results based on the implementation of the Heuristic 5 policy are presented in the sixth column of Table 3.

As expected, results show significant improvements in MEDEVAC utilization rates, average number of used beds at each MTF, Golden Hour rate, average patient response and wait times, and queue length. However, results shows no notable improvements in maximum patient response and wait times across all triage levels. Further investigation shows that maximum patient response and wait times across all triage levels fall within the same confidence region. Since all routine requests are rejected, it may indicate that these maximum response and wait times belong to patients of the same requests. These requests likely involve urgent patients and can only be seen at MTF 1. Since MEDEVAC units are more likely available to service these urgent requests, as evidence by the significant drop in average MEDEVAC utilization rates, it is possible that the maximum patient response and wait time are caused largely by the shortage of emergency beds at MTF 1.

4.4 Combined Heuristic Policies & Policy Comparisons

The heuristic policies provided valuable insights into how the MEDEVAC system operates under certain conditions. However, none of the policies, individually, can provide a serviceable solution to improving MEDEVAC system performance. As such, this thesis also explores a Heuristic 6 policy that combines the Heuristic 1-4 policies. First, requests are prioritized by triage level. Second, non-urgent requests are sent to MTF 2 to reserve MTF 1 for urgent requests. Third, the MEDEVAC system conducts a partial evacuation if a full evacuation for other requests in queue is not feasible. Finally, the MEDEVAC system suspends non-urgent request operations until all urgent request in queue have been serviced. This thesis also explores a Heuristic 7 policy that combines all Heuristic policies 1-5, which includes the rejection

of all routine requests. The performance results based on the implementation of the Heuristic 6 and 7 policies are presented in the seventh and eight column of Table 3, respectively.

As expected, the Heuristic 6 policy provides significant improvements in several performance metrics such as average number of used beds at MTF 1, average response and wait times for urgent patients, maximum response time for priority patients, maximum wait times across all triage levels, and Golden Hour rate. Although results show a significant increase in the average number of used beds at MTF 2, this is necessary in improving MEDEVAC system performance as it allows MTF 1 to focus on urgent patients that require Role 3 medical care. Furthermore, when implementing the Heuristic 7 policy, results show significant improvements in all performance metrics, excluding average MEDEVAC mission times. The Heuristic 7 policy also outperforms the Heuristic 6 policy in all performance metrics.

All policies are compared to highlight any notable contributions using confidence region plots for each performance metric. Figure 7 shows a noticeable drop in utilization rates across all MEDEVAC units for the Heuristic 5 and 7 policies. This drop in average MEDEVAC utilization rates is largely caused by the rejection of all routine requests by both policies. Excluding the Heuristic 5 and 7 policies, average MEDEVAC utilization rates are fairly identical across all policies.

In Figure 8, when compared to the baseline policy, there are significant increases in average mission times for MEDEVAC Units 1, 3, and 4, when the Heuristic 2 and 6 policies are implemented. These policies require evacuation for non-urgent requests to only MTF 2, and thus, it increases the amount of times these MEDEVAC units engage in these lengthy missions. There is also a noticeable decrease in average mission times across all MEDEVAC units when the Heuristic 5 policy is implemented. This is largely due to the decrease in the total amount of patients serviced, as a result

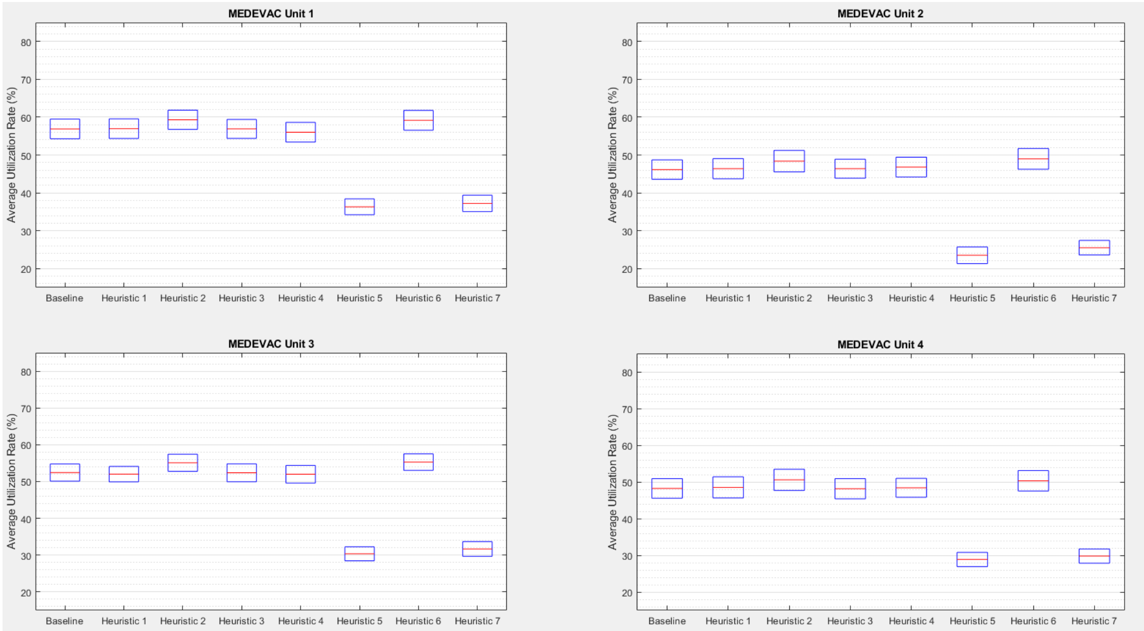

Figure 7. 95% CI Policy Comparison: Average MEDEVAC Unit Utilization Rate

of rejecting routine requests. Furthermore, MEDEVAC units are more likely able to service requests near their respective locations. Despite servicing less requests under the Heuristic 7 policy, MEDEVAC Unit 4 still shows significant increase in average mission times as it is still required that non-urgent requests are evacuated to MTF 2.

In Figure 9, when compared to the baseline policy, there is a significant improvement in the Golden Hour rate under the Heuristic 2, 5, 6, and 7 policies. This may indicate that the improvement in the Golden Hour rate is largely caused by the rejection of routine patients and reserving MTF 1 for urgent requests. Furthermore, a comparison between the Heuristic 6 and 7 policies show a greater effect in rejecting all routine requests than reserving MTF 1 for urgent requests. Although not significant, there is a slight improvement in the Golden Hour rate when implementing the Heuristic 1 and 3 policies. There is also a slight decrease in the Golden Hour rate when implementing the Heuristic 4 policy. This may be due to the shortage of emergency beds seen at MTF 1 that cause more urgent patients whose response times exceed an hour.

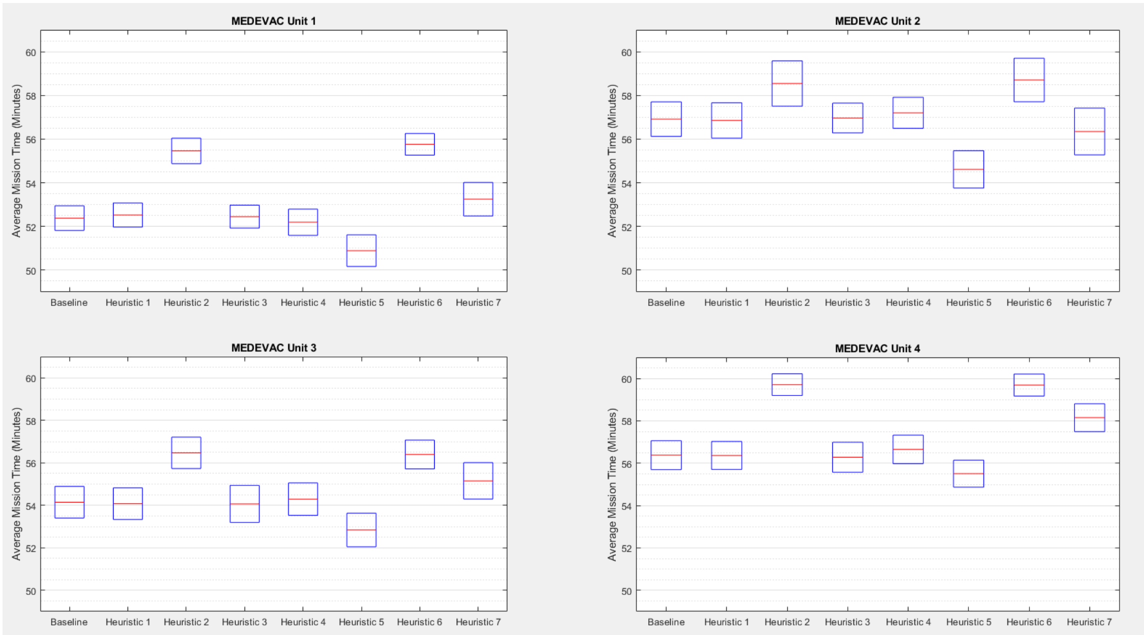

Figure 8. 95% CI Policy Comparison: Average MEDEVAC Mission Time

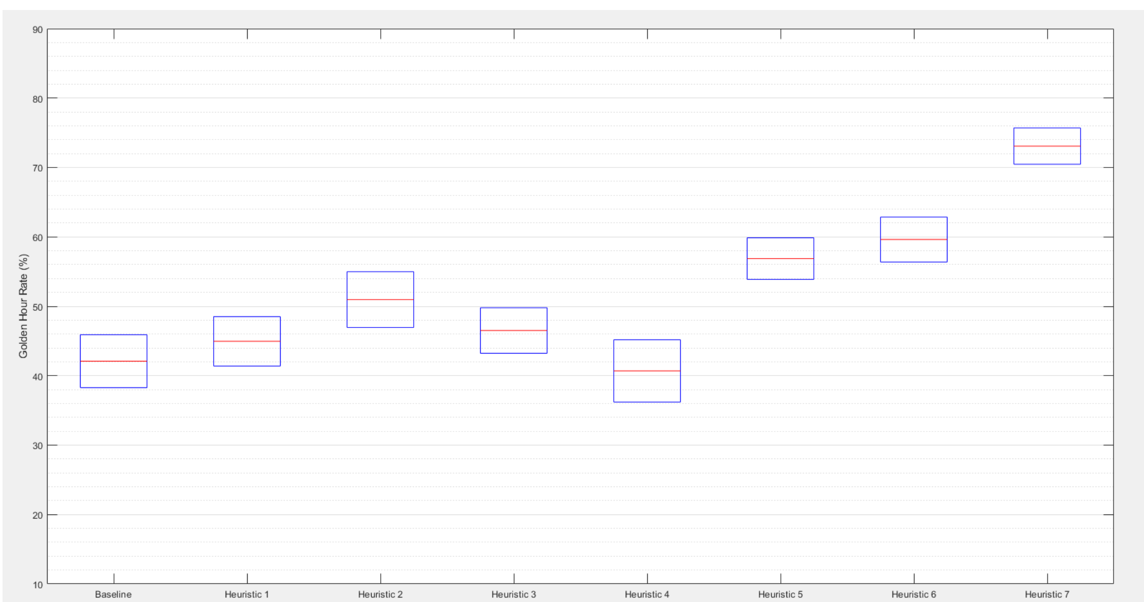

Figure 9. 95% CI Policy Comparison: Golden Hour Rate

In Figure 10, when compared to the baseline policy, there is significant improvement in patient response time for urgent patients across all policies, excluding the Heuristic 1 policy. Furthermore, there is a significant improvement in the combined Heuristic 6 and 7 policies over the other policies. This indicates that there is a positive interaction effect when policies are combined. Finally, despite the Heuristic 5 policy outperforming the Heuristic 6 policy in several categories, the Heuristic 6 policy significantly outperforms the Heuristic 5 policy in critical performance metrics.

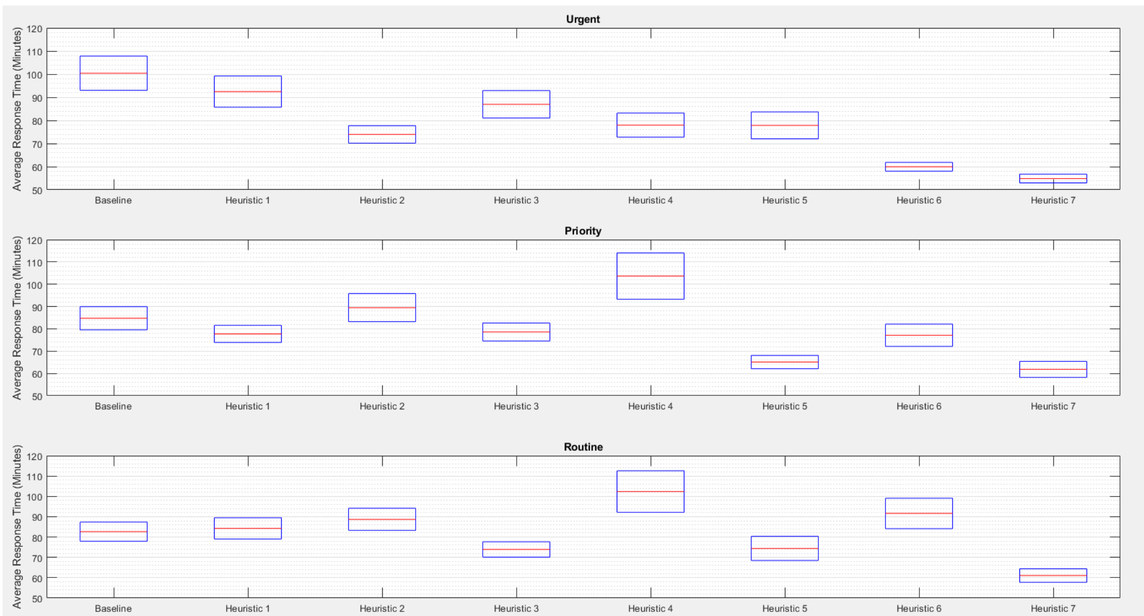

Figure 10. 95% CI Policy Comparison: Average Patient Response Time

In Figure 11, there is a significant drop in maximum response times when under the Heuristics 2, 4, 6, and 7 policies. Similar to insights gained when observing the Golden Hour Rate results in Figure 9, there is a significant improvement in performance that is caused by rejecting routine requests and reserving MTF 1 for urgent requests. When observing the plots referencing priority and routine patients, the Heuristic 7 policy significantly outperforms all other policies, mainly due to rejecting routine requests.

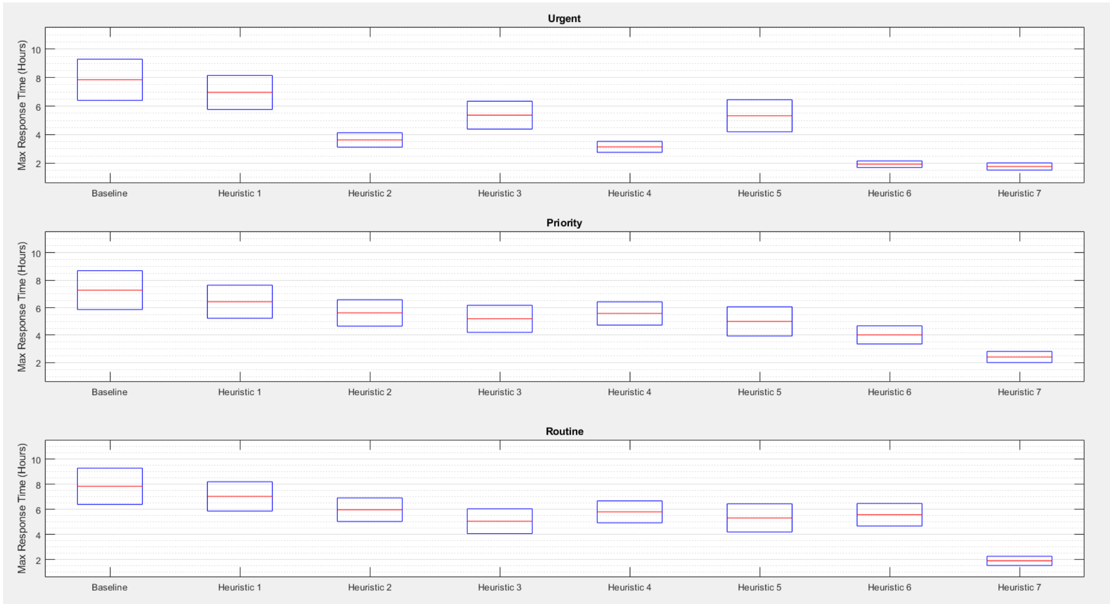

Figure 11. 95% CI Policy Comparison: Maximum Patient Response Time

4.5 Sensitivity Analysis

As seen in the results of Section 4.4, the Heuristic 6 and 7 policies yield the best overall results when compared to other explored policies. As such, sensitivity analysis is conducted on these policies to test for robustness against certain parameters. The policies are tested against alternative settings of four parameters: 1) request arrival rate, 2) maximum emergency bed capacity at each MTF, 3) average MEDEVAC flight speed, and 4) triage arrival probabilities. Results for each parameter setting are compared across both policies.

First, both policies are evaluated on four settings of request arrival rate λ: 0.5, 1 (i.e., baseline setting), 1.5, and 2. The results can be seen in Tables 4-5. Results show that the MEDEVAC system performance is highly sensitive to varying arrival rates despite implementing the improved policies of Heuristic 6 and 7. There are significant changes across most metrics for each arrival rate setting, indicating that significant changes need to be made in the current policies and/or resources to match the changes in request arrival rates.

Table 4. Heuristic 6 Sensitivity Results: Request Arrival Rates

Performance Metric	(0.5)	(1)*	(1.5)	(2)
Average MEDEVAC Utilization Rate (%)				
Unit 1	30.511 ± 2.121	59.161 ± 2.618	80.574 ± 2.113	87.069 ± 1.724
Unit 2	21.453 ± 1.905	48.979 ± 2.745	75.678 ± 2.996	84.299 ± 2.205
Unit 3	28.069 ± 2.130	55.282 ± 2.253	78.880 ± 2.364	85.745 ± 1.968
Unit 4	24.324 ± 2.171	50.312 ± 2.782	76.487 ± 2.817	85.084 ± 2.099
Average MEDEVAC Mission Time (Hours)				
Unit 1	0.910 ± 0.013	0.929 ± 0.008	0.924 ± 0.011	0.927 ± 0.012
Unit 2	0.919 ± 0.017	0.978 ± 0.017	0.981 ± 0.009	0.987 ± 0.010
Unit 3	0.920 ± 0.018	0.940 ± 0.011	0.956 ± 0.010	0.951 ± 0.007
Unit 4	0.997 ± 0.015	0.995 ± 0.009	0.998 ± 0.010	0.994 ± 0.010
Golden Hour Rate (%)	74.481 ± 4.291	59.620 ± 3.239	42.572 ± 3.373	28.158 ± 2.559
Average Patient Response Time (Hours)				
Urgent	0.897 ± 0.025	0.999 ± 0.032	1.138 ± 0.046	1.366 ± 0.070
Priority	0.967 ± 0.024	1.285 ± 0.084	1.878 ± 0.219	3.388 ± 0.488
Routine	1.003 ± 0.036	1.527 ± 0.125	3.971 ± 0.815	10.078 ± 1.058
Max Patient Response Time (Hours)				
Urgent	1.356 ± 0.075	1.926 ± 0.233	2.418 ± 0.253	3.273 ± 0.370
Priority	1.725 ± 0.180	4.017 ± 0.660	7.586 ± 1.607	13.204 ± 2.077
Routine	1.975 ± 0.247	5.581 ± 0.902	15.442 ± 3.338	37.464 ± 3.738
Average Wait Time (Hours)				
Urgent	0.035 ± 0.016	0.119 ± 0.031	0.249 ± 0.043	0.472 ± 0.076
Priority	0.054 ± 0.016	0.347 ± 0.087	0.938 ± 0.217	2.447 ± 0.491
Routine	0.074 ± 0.028	0.569 ± 0.120	3.060 ± 0.822	9.239 ± 1.059
Max Wait Time (Hours)				
Urgent	0.304 ± 0.084	0.931 ± 0.252	1.536 ± 0.263	2.476 ± 0.368
Priority	0.748 ± 0.199	2.988 ± 0.666	6.933 ± 1.737	12.296 ± 2.089
Routine	0.924 ± 0.260	4.590 ± 0.928	15.536 ± 3.850	36.908 ± 3.878
Average Queue Length	0.075 ± 0.028	0.881 ± 0.183	6.594 ± 2.054	35.257 ± 6.148
Max Queue Length	3.133 ± 0.585	9.667 ± 1.356	22.100 ± 4.279	75.767 ± 12.485
Average Beds Used				
MTF 1	1.470 ± 0.143	2.991 ± 0.196	4.212 ± 0.304	5.775 ± 0.318
MTF 2	2.242 ± 0.146	4.599 ± 0.237	6.411 ± 0.210	7.016 ± 0.234

* Baseline parameter setting

Table 5. Heuristic 7 Sensitivity Results: Request Arrival Rates

Performance Metric	(0.5)	(1)*	(1.5)	(2)
Average MEDEVAC Utilization Rate (%)				
Unit 1	19.160 ± 1.256	37.207 ± 2.170	53.685 ± 2.560	65.442 ± 1.961
Unit 2	10.450 ± 1.363	25.501 ± 1.928	40.495 ± 2.550	56.992 ± 2.544
Unit 3	15.165 ± 1.483	31.688 ± 2.001	46.955 ± 2.360	62.304 ± 2.167
Unit 4	14.221 ± 1.581	29.790 ± 1.934	44.834 ± 2.353	58.804 ± 2.581
Average MEDEVAC Mission Time (Hours)				
Unit 1	0.873 ± 0.018	0.887 ± 0.013	0.897 ± 0.011	0.904 ± 0.011
Unit 2	0.905 ± 0.029	0.939 ± 0.018	0.945 ± 0.013	0.965 ± 0.013
Unit 3	0.885 ± 0.020	0.919 ± 0.014	0.908 ± 0.010	0.931 ± 0.009
Unit 4	0.972 ± 0.016	0.969 ± 0.011	0.978 ± 0.012	0.977 ± 0.012
Golden Hour Rate (%)	78.568 ± 4.627	73.078 ± 2.619	62.104 ± 4.288	44.572 ± 3.488
Average Patient Response Time (Hours)				
Urgent	0.858 ± 0.022	0.914 ± 0.032	1.010 ± 0.049	1.236 ± 0.068
Priority	0.909 ± 0.018	1.030 ± 0.060	1.287 ± 0.135	2.019 ± 0.344
Routine	0.927 ± 0.025	1.017 ± 0.055	1.239 ± 0.128	2.303 ± 0.518
Max Patient Response Time (Hours)				
Urgent	1.240 ± 0.072	1.766 ± 0.248	2.260 ± 0.248	3.178 ± 0.351
Priority	1.415 ± 0.071	2.412 ± 0.404	4.086 ± 0.776	8.249 ± 1.561
Routine	1.338 ± 0.086	1.903 ± 0.363	3.651 ± 0.792	7.608 ± 1.506
Average Wait Time (Hours)				
Urgent	0.012 ± 0.010	0.056 ± 0.032	0.143 ± 0.042	0.355 ± 0.073
Priority	0.017 ± 0.010	0.115 ± 0.062	0.361 ± 0.131	1.103 ± 0.345
Routine	0.011 ± 0.008	0.089 ± 0.060	0.314 ± 0.125	1.361 ± 0.510
Max Wait Time (Hours)				
Urgent	0.136 ± 0.088	0.757 ± 0.278	1.350 ± 0.260	2.380 ± 0.359
Priority	0.290 ± 0.144	1.429 ± 0.401	3.141 ± 0.778	7.436 ± 1.624
Routine	0.170 ± 0.101	0.863 ± 0.419	2.686 ± 0.803	6.779 ± 1.514
Average Queue Length	0.164 ± 0.024	0.274 ± 0.060	0.763 ± 0.234	2.688 ± 0.859
Max Queue Length	1.500 ± 0.278	4.200 ± 1.010	7.700 ± 1.553	14.167 ± 2.376
Average Beds Used				
MTF 1	1.463 ± 0.142	2.975 ± 0.195	4.197 ± 0.307	5.768 ± 0.319
MTF 2	1.363 ± 0.116	2.839 ± 0.160	3.928 ± 0.152	4.928 ± 0.164

* Baseline parameter setting

Second, both policies are evaluated on four settings of maximum emergency bed capacity at each MTF: 7, 10 (i.e., baseline setting), 13, and 16 beds. The MEDEVAC system performance results under these settings are presented in Tables 6-7. Results show no notable changes in MEDEVAC unit performance. However, when the maximum bed capacity is decreased from the baseline level, there is a significant increase in patient response times across all triage levels for both heuristic policies. When the capacity is increased from the baseline level, significant improvements in patient response time continue at each setting under the Heuristic 6 policy. At a maximum capacity of 13 emergency beds, there is a significant improvement in response times for priority patients. At a maximum capacity of 16 emergency beds, improvements in patient response times for urgent and routine patients are notable. However, there does not appear to be any notable improvement in results when implementing the superior Heuristic 7 policy. Although the increase in maximum bed capacity shows no notable improvement in MEDEVAC system performance under the Heuristic 7 policy, this is a possible indication that other system factors may have stunted further improvements in performance.

Third, both policies are evaluated on four settings of average MEDEVAC flight speed. The four settings are chosen at an interval of 13 knots up to the HH-60M Black Hawk's maximum speed of 191 knots: 152 (i.e., baseline setting), 165, 178, and 191 knots. The results can be seen in Tables 8-9. When the Heuristic 6 policy is implemented, results show significant improvements in average mission times for MEDEVAC Units 1, 3, and 4 at an average flight speed of 165 knots. Significant improvements for average mission times for MEDEVAC Unit 2 and Golden Hour rate are not seen until the average flight speed is increased to 178 knots. At 178 knots, average mission times for MEDEVAC Unit 1 and 4 significantly improve again in comparison to average flight speed at 165 knots. Results also reveal that notable im-

Table 6. Heuristic 6 Sensitivity Results: Maximum Bed Capacity

Performance Metric	(7)	(10)*	(13)	(16)
Average MEDEVAC Utilization Rate (%)				
Unit 1	57.925 ± 2.290	59.161 ± 2.618	59.341 ± 2.696	59.236 ± 2.615
Unit 2	47.821 ± 2.988	48.979 ± 2.745	49.121 ± 2.707	49.160 ± 2.765
Unit 3	53.980 ± 2.519	55.282 ± 2.253	54.642 ± 2.261	54.695 ± 2.251
Unit 4	50.211 ± 2.807	50.312 ± 2.782	51.178 ± 2.827	51.249 ± 2.854
Average MEDEVAC Mission Time (Hours)				
Unit 1	0.920 ± 0.009	0.929 ± 0.008	0.926 ± 0.009	0.927 ± 0.009
Unit 2	0.971 ± 0.013	0.978 ± 0.017	0.980 ± 0.017	0.978 ± 0.016
Unit 3	0.941 ± 0.013	0.940 ± 0.011	0.946 ± 0.014	0.948 ± 0.012
Unit 4	0.989 ± 0.010	0.995 ± 0.009	0.996 ± 0.010	0.995 ± 0.010
Golden Hour Rate (%)	52.917 ± 3.586	59.620 ± 3.239	58.934 ± 3.597	58.925 ± 3.546
Average Patient Response Time (Hours)				
Urgent	1.208 ± 0.079	0.999 ± 0.032	0.977 ± 0.020	0.975 ± 0.019
Priority	2.036 ± 0.372	1.285 ± 0.084	1.143 ± 0.041	1.116 ± 0.031
Routine	2.879 ± 0.651	1.527 ± 0.125	1.389 ± 0.093	1.360 ± 0.090
Max Patient Response Time (Hours)				
Urgent	3.290 ± 0.386	1.926 ± 0.233	1.652 ± 0.128	1.613 ± 0.079
Priority	8.477 ± 2.257	4.017 ± 0.660	2.721 ± 0.314	2.280 ± 0.175
Routine	12.821 ± 2.572	5.581 ± 0.902	4.285 ± 0.551	4.131 ± 0.508
Average Wait Time (Hours)				
Urgent	0.342 ± 0.081	0.119 ± 0.031	0.094 ± 0.018	0.090 ± 0.014
Priority	1.107 ± 0.370	0.347 ± 0.087	0.203 ± 0.043	0.175 ± 0.029
Routine	1.932 ± 0.645	0.569 ± 0.120	0.430 ± 0.088	0.399 ± 0.085
Max Wait Time (Hours)				
Urgent	2.439 ± 0.377	0.931 ± 0.252	0.625 ± 0.138	0.584 ± 0.067
Priority	7.554 ± 2.268	2.988 ± 0.666	1.688 ± 0.323	1.217 ± 0.156
Routine	11.939 ± 2.572	4.590 ± 0.928	3.297 ± 0.556	3.166 ± 0.522
Average Queue Length	2.631 ± 0.923	0.881 ± 0.183	0.715 ± 0.152	0.693 ± 0.151
Max Queue Length	14.333 ± 2.285	9.667 ± 1.356	8.700 ± 1.233	8.633 ± 1.160
Average Beds Used				
MTF 1	2.965 ± 0.194	2.991 ± 0.196	2.997 ± 0.197	2.998 ± 0.197
MTF 2	4.159 ± 0.193	4.599 ± 0.237	4.767 ± 0.253	4.842 ± 0.259

* Baseline parameter setting

Table 7. Heuristic 7 Sensitivity Results: Maximum Bed Capacity

Performance Metric	(7)	(10)*	(13)	(16)
Average MEDEVAC Utilization Rate (%)				
Unit 1	36.558 ± 2.099	37.207 ± 2.170	37.401 ± 2.194	37.422 ± 2.200
Unit 2	24.799 ± 2.058	25.501 ± 1.928	25.655 ± 2.042	25.720 ± 2.010
Unit 3	32.002 ± 1.741	31.688 ± 2.001	31.677 ± 1.930	31.647 ± 1.945
Unit 4	29.836 ± 1.990	29.790 ± 1.934	29.957 ± 1.962	29.995 ± 1.974
Average MEDEVAC Mission Time (Hours)				
Unit 1	0.883 ± 0.013	0.887 ± 0.013	0.893 ± 0.014	0.892 ± 0.014
Unit 2	0.937 ± 0.019	0.939 ± 0.018	0.939 ± 0.018	0.942 ± 0.019
Unit 3	0.913 ± 0.014	0.919 ± 0.014	0.917 ± 0.014	0.916 ± 0.015
Unit 4	0.975 ± 0.011	0.969 ± 0.011	0.972 ± 0.011	0.973 ± 0.011
Golden Hour Rate (%)	62.235 ± 3.224	73.078 ± 2.619	74.142 ± 2.615	74.132 ± 2.744
Average Patient Response Time (Hours)				
Urgent	1.133 ± 0.079	0.914 ± 0.032	0.892 ± 0.017	0.888 ± 0.013
Priority	1.405 ± 0.147	1.030 ± 0.060	0.993 ± 0.037	0.984 ± 0.025
Routine	1.246 ± 0.149	1.017 ± 0.055	1.021 ± 0.043	1.016 ± 0.036
Max Patient Response Time (Hours)				
Urgent	3.145 ± 0.391	1.766 ± 0.248	1.475 ± 0.130	1.437 ± 0.082
Priority	4.884 ± 0.919	2.412 ± 0.404	1.994 ± 0.260	1.935 ± 0.195
Routine	3.723 ± 0.880	1.903 ± 0.363	1.795 ± 0.253	1.725 ± 0.158
Average Wait Time (Hours)				
Urgent	0.282 ± 0.079	0.056 ± 0.032	0.031 ± 0.016	0.027 ± 0.008
Priority	0.497 ± 0.149	0.115 ± 0.062	0.072 ± 0.039	0.063 ± 0.024
Routine	0.320 ± 0.147	0.089 ± 0.060	0.078 ± 0.041	0.072 ± 0.029
Max Wait Time (Hours)				
Urgent	2.300 ± 0.381	0.757 ± 0.278	0.408 ± 0.144	0.376 ± 0.084
Priority	4.034 ± 0.949	1.429 ± 0.401	0.930 ± 0.267	0.869 ± 0.200
Routine	2.701 ± 0.881	0.863 ± 0.419	0.714 ± 0.290	0.629 ± 0.182
Average Queue Length	0.678 ± 0.175	0.274 ± 0.060	0.230 ± 0.037	0.221 ± 0.025
Max Queue Length	6.833 ± 1.272	4.200 ± 1.010	3.567 ± 0.812	3.500 ± 0.714
Average Beds Used				
MTF 1	2.956 ± 0.193	2.975 ± 0.195	2.949 ± 0.176	2.982 ± 0.196
MTF 2	2.575 ± 0.137	2.839 ± 0.160	0.045 ± 0.010	2.985 ± 0.184

* Baseline parameter setting

provements in average patient response times across all triage levels are not observed until the average flight speed is increased to the maximum speed of 191 knots. When the Heuristic 7 policy is implemented, results also show significant improvement in average mission times for MEDEVAC Units 3 and 4 at an average flight speed of 165 knots. At 178 knots, significant improvements in the Golden Hour rate and the average mission times for MEDEVAC Units 1 and 2 are observed. Furthermore, results reveal significant improvement in mission times for MEDEVAC Unit 4 when compared to mission times at an average flight speed of 165 knots. Results, however, also reveal no notable improvements in patient response and wait times, even at maximum flight speed. These improvements in mission times, when implementing either policy, may be driven largely by the evacuation missions to MTF 2 for non-urgent requests. Furthermore, since increase in average flight speed does not provide any notable improvements in patient service times, it may suggest that, at least for this scenario, there could be other operational factors, such as mission preparation, offload, and load times, that could be improved to benefit system performance.

Finally, both policies are evaluated on three settings of patient triage probabilities, of which includes the baseline setting. The second setting entails the servicing of urgent or priority patient at equal probabilities of $\frac{1}{4}$ and servicing of routine patients at a probability of $\frac{2}{4}$. The last setting entails the servicing of patients of any triage level at a probability of $\frac{1}{3}$. The results can be seen in Tables 10-11. For both heuristic policies, results show significant decreases in patient response times, wait times, and queue length. The significant decrease in average MEDEVAC utilization rates and average mission times may indicate that the MEDEVAC system is forced to a standstill due to the large number of urgent requests arriving into the system. MEDEVAC operations are delayed until emergency beds become available at MTF 1. The heuristic policies enforce a suspension in non-urgent operations until no urgent requests are in queue,

Table 8. Heuristic 6 Sensitivity Results: Average MEDEVAC Flight Speed

Performance Metric	(152)*	(165)	(178)	(191)
Average MEDEVAC Utilization Rate (%)				
Unit 1	59.161 ± 2.618	57.447 ± 2.513	56.189 ± 2.329	55.252 ± 2.438
Unit 2	48.979 ± 2.745	47.705 ± 2.682	45.833 ± 2.692	44.067 ± 2.376
Unit 3	55.282 ± 2.253	53.464 ± 2.181	52.149 ± 2.211	50.580 ± 2.253
Unit 4	50.312 ± 2.782	48.886 ± 2.830	47.771 ± 2.714	47.199 ± 2.672
Average MEDEVAC Mission Time (Hours)				
Unit 1	0.929 ± 0.008	0.902 ± 0.008	0.876 ± 0.007	0.857 ± 0.008
Unit 2	0.978 ± 0.017	0.952 ± 0.014	0.923 ± 0.013	0.901 ± 0.012
Unit 3	0.940 ± 0.011	0.913 ± 0.012	0.894 ± 0.011	0.870 ± 0.012
Unit 4	0.995 ± 0.009	0.962 ± 0.010	0.934 ± 0.010	0.911 ± 0.009
Golden Hour Rate (%)	59.620 ± 3.239	63.119 ± 3.574	67.315 ± 3.494	71.013 ± 3.017
Average Patient Response Time (Hours)				
Urgent	0.999 ± 0.032	0.964 ± 0.029	0.941 ± 0.029	0.916 ± 0.029
Priority	1.285 ± 0.084	1.224 ± 0.077	1.181 ± 0.076	1.128 ± 0.067
Routine	1.527 ± 0.125	1.441 ± 0.114	1.366 ± 0.105	1.304 ± 0.098
Max Patient Response Time (Hours)				
Urgent	1.926 ± 0.233	1.863 ± 0.229	1.806 ± 0.229	1.771 ± 0.227
Priority	4.017 ± 0.660	3.869 ± 0.629	3.619 ± 0.620	3.443 ± 0.581
Routine	5.581 ± 0.902	5.155 ± 0.888	4.941 ± 0.902	4.573 ± 0.819
Average Wait Time (Hours)				
Urgent	0.119 ± 0.031	0.108 ± 0.029	0.104 ± 0.030	0.097 ± 0.029
Priority	0.347 ± 0.087	0.314 ± 0.080	0.294 ± 0.079	0.261 ± 0.070
Routine	0.569 ± 0.120	0.512 ± 0.111	0.463 ± 0.102	0.423 ± 0.094
Max Wait Time (Hours)				
Urgent	0.931 ± 0.252	0.901 ± 0.246	0.878 ± 0.247	0.860 ± 0.246
Priority	2.988 ± 0.666	2.877 ± 0.635	2.660 ± 0.627	2.547 ± 0.604
Routine	4.590 ± 0.928	4.146 ± 0.905	3.993 ± 0.908	3.652 ± 0.825
Average Queue Length	0.881 ± 0.183	0.800 ± 0.169	0.724 ± 0.154	0.669 ± 0.143
Max Queue Length	9.667 ± 1.356	9.433 ± 1.348	8.933 ± 1.281	8.667 ± 1.241
Average Beds Used				
MTF 1	2.991 ± 0.196	2.972 ± 0.195	2.956 ± 0.194	2.943 ± 0.193
MTF 2	4.599 ± 0.237	4.506 ± 0.233	4.433 ± 0.226	4.381 ± 0.221

* Baseline parameter setting

Table 9. **Heuristic 7 Sensitivity Results: Average MEDEVAC Flight Speed**

Performance Metric	(152)*	(165)	(178)	(191)
Average MEDEVAC Utilization Rate (%)				
Unit 1	37.207 ± 2.170	36.395 ± 2.194	35.526 ± 2.131	34.847 ± 2.057
Unit 2	25.501 ± 1.928	24.738 ± 1.892	23.904 ± 1.808	23.449 ± 1.830
Unit 3	31.688 ± 2.001	30.812 ± 1.893	30.178 ± 1.973	29.475 ± 1.970
Unit 4	29.790 ± 1.934	28.756 ± 1.894	28.165 ± 1.841	27.474 ± 1.792
Average MEDEVAC Mission Time (Hours)				
Unit 1	0.887 ± 0.013	0.866 ± 0.012	0.845 ± 0.012	0.828 ± 0.010
Unit 2	0.939 ± 0.018	0.912 ± 0.017	0.887 ± 0.015	0.868 ± 0.015
Unit 3	0.919 ± 0.014	0.891 ± 0.013	0.871 ± 0.013	0.851 ± 0.012
Unit 4	0.969 ± 0.011	0.940 ± 0.011	0.915 ± 0.009	0.894 ± 0.010
Golden Hour Rate (%)	73.078 ± 2.619	77.279 ± 2.548	81.057 ± 2.128	83.578 ± 2.022
Average Patient Response Time (Hours)				
Urgent	0.914 ± 0.032	0.891 ± 0.032	0.871 ± 0.032	0.852 ± 0.032
Priority	1.030 ± 0.060	0.994 ± 0.059	0.965 ± 0.058	0.941 ± 0.057
Routine	1.017 ± 0.055	0.987 ± 0.057	0.956 ± 0.055	0.935 ± 0.055
Max Patient Response Time (Hours)				
Urgent	1.766 ± 0.248	1.721 ± 0.250	1.676 ± 0.250	1.633 ± 0.254
Priority	2.412 ± 0.404	2.334 ± 0.407	2.250 ± 0.404	2.168 ± 0.384
Routine	1.903 ± 0.363	1.850 ± 0.382	1.772 ± 0.372	1.730 ± 0.366
Average Wait Time (Hours)				
Urgent	0.056 ± 0.032	0.054 ± 0.031	0.053 ± 0.031	0.051 ± 0.031
Priority	0.115 ± 0.062	0.105 ± 0.061	0.098 ± 0.060	0.094 ± 0.060
Routine	0.089 ± 0.060	0.080 ± 0.058	0.073 ± 0.057	0.070 ± 0.056
Max Wait Time (Hours)				
Urgent	0.757 ± 0.278	0.742 ± 0.277	0.740 ± 0.276	0.716 ± 0.277
Priority	1.429 ± 0.401	1.368 ± 0.395	1.323 ± 0.394	1.261 ± 0.379
Routine	0.863 ± 0.419	0.796 ± 0.409	0.734 ± 0.407	0.719 ± 0.402
Average Queue Length	0.274 ± 0.060	0.265 ± 0.059	0.258 ± 0.059	0.251 ± 0.059
Max Queue Length	4.200 ± 1.010	4.067 ± 0.939	3.933 ± 0.939	3.900 ± 0.922
Average Beds Used				
MTF 1	2.975 ± 0.195	2.957 ± 0.194	2.942 ± 0.193	2.928 ± 0.192
MTF 2	2.839 ± 0.160	2.798 ± 0.158	2.760 ± 0.156	2.729 ± 0.154

* Baseline parameter setting

resulting in an underutilized MTF2 and an increase in non-urgent requests in queue. This circumstance highlights the importance of the MTF 1's role in the success of a MEDEVAC system. Improvements in the current policies and/or resources must be made to match the varying triage demands.

Table 10. Heuristic 6 Sensitivity Results: Triage Arrival Probabilities

Performance Metric	$(\frac{1}{7},\frac{2}{7},\frac{4}{7})^*$	$(\frac{1}{4},\frac{1}{4},\frac{2}{4})$	$(\frac{1}{3},\frac{1}{3},\frac{1}{3})$
Average MEDEVAC Utilization Rate (%)			
Unit 1	59.161 ± 2.618	57.122 ± 2.504	52.289 ± 2.708
Unit 2	48.979 ± 2.745	48.450 ± 2.389	41.988 ± 2.836
Unit 3	55.282 ± 2.253	53.677 ± 2.448	48.344 ± 2.707
Unit 4	50.312 ± 2.782	50.070 ± 2.781	45.041 ± 2.750
Average MEDEVAC Mission Time (Hours)			
Unit 1	0.929 ± 0.008	0.910 ± 0.012	0.886 ± 0.014
Unit 2	0.978 ± 0.017	0.970 ± 0.012	0.964 ± 0.015
Unit 3	0.940 ± 0.011	0.935 ± 0.012	0.920 ± 0.016
Unit 4	0.995 ± 0.009	0.975 ± 0.010	0.961 ± 0.012
Golden Hour Rate (%)	59.620 ± 3.239	48.154 ± 4.005	30.119 ± 4.398
Average Patient Response Time (Hours)			
Urgent	0.999 ± 0.032	1.269 ± 0.090	2.287 ± 0.369
Priority	1.285 ± 0.084	1.688 ± 0.248	3.879 ± 0.959
Routine	1.527 ± 0.125	2.285 ± 0.442	5.001 ± 1.369
Max Patient Response Time (Hours)			
Urgent	1.926 ± 0.233	3.435 ± 0.446	6.255 ± 0.727
Priority	4.017 ± 0.660	5.778 ± 1.069	13.946 ± 3.273
Routine	5.581 ± 0.902	8.998 ± 2.070	16.626 ± 3.686
Average Wait Time (Hours)			
Urgent	0.119 ± 0.031	0.399 ± 0.092	1.438 ± 0.371
Priority	0.347 ± 0.087	0.773 ± 0.248	2.972 ± 0.969
Routine	0.569 ± 0.120	1.330 ± 0.438	4.097 ± 1.397
Max Wait Time (Hours)			
Urgent	0.931 ± 0.252	2.668 ± 0.442	5.476 ± 0.734
Priority	2.988 ± 0.666	4.964 ± 1.076	13.039 ± 3.246
Routine	4.590 ± 0.928	8.119 ± 2.050	15.589 ± 3.693
Average Queue Length	0.881 ± 0.183	2.038 ± 0.679	9.248 ± 4.067
Max Queue Length	9.667 ± 1.356	13.967 ± 2.179	27.967 ± 7.113
Average Beds Used			
MTF 1	2.991 ± 0.196	4.960 ± 0.315	6.795 ± 0.331
MTF 2	4.599 ± 0.237	3.568 ± 0.201	2.519 ± 0.276

* Baseline parameter setting

Table 11. Heuristic 7 Sensitivity Results: Triage Arrival Probabilities

Performance Metric	$(\frac{1}{7}, \frac{2}{7}, \frac{4}{7})^*$	$(\frac{1}{4}, \frac{1}{4}, \frac{2}{4})$	$(\frac{1}{3}, \frac{1}{3}, \frac{1}{3})$
Average MEDEVAC Utilization Rate (%)			
Unit 1	37.207 ± 2.170	40.365 ± 2.199	44.350 ± 2.348
Unit 2	25.501 ± 1.928	28.621 ± 2.218	33.010 ± 2.048
Unit 3	31.688 ± 2.001	35.452 ± 1.869	40.227 ± 2.091
Unit 4	29.790 ± 1.934	33.081 ± 2.206	36.065 ± 1.944
Average MEDEVAC Mission Time (Hours)			
Unit 1	0.887 ± 0.013	0.882 ± 0.014	0.868 ± 0.015
Unit 2	0.939 ± 0.018	0.935 ± 0.016	0.941 ± 0.017
Unit 3	0.919 ± 0.014	0.904 ± 0.013	0.903 ± 0.014
Unit 4	0.969 ± 0.011	0.954 ± 0.012	0.946 ± 0.010
Golden Hour Rate (%)	73.078 ± 2.619	59.028 ± 3.624	33.830 ± 4.787
Average Patient Response Time (Hours)			
Urgent	0.914 ± 0.032	1.189 ± 0.084	2.252 ± 0.376
Priority	1.030 ± 0.060	1.474 ± 0.228	3.679 ± 0.948
Routine	1.017 ± 0.055	1.530 ± 0.257	4.795 ± 1.883
Max Patient Response Time (Hours)			
Urgent	1.766 ± 0.248	3.352 ± 0.451	6.285 ± 0.747
Priority	2.412 ± 0.404	4.974 ± 0.945	13.552 ± 3.401
Routine	1.903 ± 0.363	4.407 ± 1.004	12.353 ± 3.286
Average Wait Time (Hours)			
Urgent	0.056 ± 0.032	0.335 ± 0.086	1.402 ± 0.378
Priority	0.115 ± 0.062	0.575 ± 0.229	2.760 ± 0.942
Routine	0.089 ± 0.060	0.588 ± 0.255	3.846 ± 1.889
Max Wait Time (Hours)			
Urgent	0.757 ± 0.278	2.608 ± 0.449	5.444 ± 0.736
Priority	1.429 ± 0.401	4.165 ± 0.962	12.563 ± 3.397
Routine	0.863 ± 0.419	3.621 ± 1.017	11.337 ± 3.290
Average Queue Length	0.274 ± 0.060	0.836 ± 0.273	5.688 ± 2.570
Max Queue Length	4.200 ± 1.010	8.067 ± 1.342	19.000 ± 4.226
Average Beds Used			
MTF 1	2.975 ± 0.195	4.947 ± 0.315	6.792 ± 0.333
MTF 2	2.839 ± 0.160	2.181 ± 0.145	1.914 ± 0.203

* Baseline parameter setting

V. Conclusions and Recommendations

When a 9-line MEDEVAC request is submitted, MEDEVAC planners must assess the current available resources and determine the best course of action to ensure that casualties are evacuated quickly and provided the proper medical care. MEDEVAC planners must also consider the state of the MEDEVAC system as it prepares to service future requests. An efficient allocation of MEDEVAC resources may prove to be beneficial in the success of an operation. However, external factors may hinder MEDEVAC system performance. Specifically, there are limitations to the capabilities and capacities of the MTFs. Such limitations could significantly impact how patients are provided medical care. Several papers in the current MEDEVAC literature assume MTFs have sufficient capacity of emergency beds and are capable of treating any patient, regardless of the type of injury. These assumptions allow for model tractability in order to determine high-quality policies. However, these assumptions are unrealistic in some situations (e.g., high-intensity combat operations) and may prevent real MEDEVAC systems from implementing the recommended policies.

This thesis develops a simulation model of a MEDEVAC dispatching and delivery system that considers the MTF limitations. A sufficient amount of stress is placed on the MTFs to evaluate their impact on MEDEVAC system performance. While incorporating a realistic arrival behavior of requests via a Hawkes process, this thesis applies the simulation model on a notional scenario of Bosnia-Herzegovina during the post-Bosnian war. The simulation is ran for a 72-hour period and is replicated 30 times to generate an acceptable estimate for the metrics used to evaluate the MEDEVAC system performance.

Under the baseline policy, results reveal an overwhelmed Role 3 MTF. Results also show an average response time of 1.67 hours, a maximum response time of 7.87 hours, and Golden Hour rate of 42.1% for urgent patients. These results indicate that the

MEDEVAC system, under the baseline policy, fails to meet the standards set by the Golden Hour mandate. Thus, this thesis explores seven alternative policies to gain insights and ultimately improve the MEDEVAC system performance. Comparisons of these policies reveal that Heuristic 6 and 7 policies result in significant improvements over the baseline policy, outperforming the other explored policies. However, the Heuristic 7 policy, which is the superior policy between the two, imposes the rejection of all routine requests that arrive into the MEDEVAC system. Although this practice is feasible under extreme conditions, MEDEVAC planners should still consider their moral obligations and the impact this practice has towards morale of military personnel downrange.

Despite significant improvements from both policies, significant changes in the current policies and/or resources must be made to match the varying request arrivals and triage demands. Regardless, the insights gained from this thesis highlight the substantial impact that the limitations of an MTF, particularly one that provides Role 3 medical care, have on the performance of a MEDEVAC system.

Future research should acknowledge the limitations of an MTF to determine more realistic policies that could improve MEDEVAC system performance. The simulation model in this thesis can be developed further to incorporate other factors, such as the utilization of standby MEDEVAC units and the redeployment of MEDEVAC units (i.e., MEDEVAC units can service the next set of requests in queue immediately after patient care is transferred to the MTF staff), and/or continue to explore alternative solutions to circumvent the limitations of the MTFs. Furthermore, along with advanced stochastic optimization techniques such as Markov decision processes and approximate dynamic programming, the simulation model developed in this thesis should be utilized to determine high-quality policies to improve MEDEVAC system performance.

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14. ABSTRACT

The location, allocation, and utilization of military medical evacuation (MEDEVAC) resources significantly impact the quality and timeliness of medical care to injured troops. In 2009, Secretary of Defense Robert Gates introduced the Golden Hour mandate that entails the evacuation of critically-injured troops to military treatment facilities (MTFs) within an hour to prevent further complications. To develop high-quality policies that improve MEDEVAC system performance, several papers in the current literature assume that MTFs have both the capacity and capability of treating any patient, regardless of the type of injury. However, these assumptions are unrealistic when conducting high-intensity operations. While acknowledging MTF limitations, this thesis simulates the MEDEVAC dispatching and delivery system to evaluate the impact that MTF limitations have on system performance. Furthermore, this thesis adopts a realistic approach to modeling request arrival behavior via a Hawkes process. Results indicate that the MEDEVAC system, under the baseline policy, fails to meet the standard set by the Golden Hour mandate. As such, this thesis explores simple heuristic policies that seek to improve system performance. The insights gained from these explored policies highlight the substantial impact MTFs have on MEDEVAC systems and should be considered in future research.

15. SUBJECT TERMS

medical evacuation, simulation, hawkes process

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