AMERICAN UNIVERSITY OF BEIRUT

DECISION SUPPORT FOR SINGLE AND MULTI-HOSPITAL EVACUATION AND EMERGENCY RESPONSE

by
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AN ABSTRACT OF THE THESIS OF

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This paper studies hospital evacuation planning which is a crucial part of a hospital's emergency management plan. During the evacuation of a hospital, patients must be moved from the building to a staging area, where they wait until they can be loaded onto a vehicle and transported to alternate care facilities. Patients need assistance and medical care throughout this process, and the level of care and assistance they require is dependent on the patient's condition. Furthermore this process must be accomplished under limited resources, such as medical transport teams and vehicle fleet size among others.

We develop two evacuation models, the first model deals with the evacuation of a single hospital, while the second model deals with the simultaneous evacuation of several hospitals. In both models the objective will be to minimize the cumulative transportation and threat risks of the patients. The patients in the evacuating hospital would require aid from the staff in order to be moved to the staging area, and then moved outside the building where they will be loaded to the available vehicles. So the hospital building evacuation and the patient’s transportation to the receiving hospitals are dependent.

The resulting models are integer programs, with complex structure. The first case study will be based on the evacuation of a large regional hospital. The second case study will be based on the evacuation of several hospitals that reside within the same area. We then discuss some performance measures related to the models’ objective functions and the optimal values simulated by the models.

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CHAPTER 1

INTRODUCTION AND MOTIVATION

Natural disasters around the globe have been occurring more frequently. According to the EM-DAT which is The International Disaster Database, the number of incidents throughout the years have increased drastically [1]. When comparing the number of disasters that took place in 1970 versus the number of disasters in 2010; the increase was very staggering, leaping from 80 disasters in 1970 to 550 disasters in 2010 [1]. With the increase in the frequency of natural disasters, it is only ordinary that the total number of fatalities per year due to those disasters is increasing. Although it is worth mentioning that the average number of people passing away per natural disaster has decreased.

Care facilities are one of the most important and needed components when any natural or human initiated disaster takes place. However upon further inspection, it was discovered that a lot of fatalities during a natural/human-caused disaster occur in care facilities. For instance according to a study in South Korea, due to natural disasters that took place between year 2000 and year 2009, the number of fatalities in hospitals and care facilities was 1,708 within the area under study [2], only patients that were already in those care facilities when the disaster occurred, and passed away were accounted for in this study. The following figure summarizes the number of casualties in each location which totaled up to 1,708.

Death tally in care facilities from disasters Nationwide in South Korea from 2000-2009	
Location	Number of Casualties
Gyunggi	289
Chungnam	189
Gyeongbuk	179
Gyeongnam	173
Gangwon	170
Other locations	708
Total	1,708

Figure 1: Death tally in care facilities from disasters nationwide in South Korea from 2000-2009

Another example which took more media coverage and attention worldwide, was hurricane Katrina which struck the US Gulf Coast on august 29, 2005. The death toll due to Hurricane Katrina in Louisiana was 877 deaths, 295 (34%) of which died in care facilities (hospitals and nursing homes). The 295 deceased individuals were already admitted in these care facilities when the disaster took place, and not admitted afterwards [5].

Given the dire need of hospitals during a disaster, hospitals' operators more often than not prefer and decide against shutting down the hospitals' operations, for both humanitarian and economical purposes [3]. However, given the high percentages of fatalities that took place in care facilities during previous disasters, these operators as well as the general population need to stop seeing hospitals and care facilities as a resort only, but also realize that hospitals sometimes need to be evacuated rather than receive patients. In other words, hospital evacuation only occurs if hospitals are also under major threat otherwise they are an integral part of any emergency plan. The type of threat (hurricane versus a chemical leak) that hits a given area will have an influence on the number of hospitals affected by this disaster, and that is in need of being evacuated [3].

Haphazard evacuation of a hospital will cause more losses than when an adequate emergency plan exists. As such an emergency order was given out by the Department of Health and Environmental Control in several states in the US, requiring all hospitals to devise an emergency plan that contains the following components, a sheltering strategy, and an evacuation and transportation team plan. Moreover, the US Environmental Protection Agency conducted a study in Las Vegas on a span of 13 years, it considered 500 events or disasters that entailed more than 25 persons to evacuate. This study showed that 1,140,000 persons were evacuated in these events out of which 100 passed away from causes related to the evacuation procedure itself and not the disaster that caused the evacuation [6]. Thus, it is established that hospitals sometimes need to be evacuated, and an adequate emergency plan must be formulated to prevent any unnecessary and needless casualties.

The importance of hospital evacuation is also underlined by the hospital accreditation standards which requires hospitals to develop evacuation plans [7]. Moreover, as of recent years, chemical leaks and terrorist attacks have become major concerns [3]. This entails that all hospitals must have an emergency plan irrespective of their location, and not only the ones located in areas where natural disasters are prone to occur.

As such in this thesis dissertation, a planning and decision support models for a single and multi-hospital evacuation will be introduced and analyzed. Planning the evacuation of a hospital is much more complicated than the planning for the evacuation of other types of facilities, since there is one major difference, which is the special needs of the evacuees. In a normal building or area evacuation schemes, the evacuees will not need any assistance and will be safe once they leave the building/area and thus there and then evacuation stops. Hospital patients which are evacuated will require assistance when leaving the building, medical attention and treatment during the evacuation process which does not only involve leaving the evacuated hospital, but also their transportation to alternative care facilities; where the type of patients that these facilities can cater for is a factor along with the availability of beds for each type of patients in each of these facilities. Moreover, while many studies have targeted the issue of mass population or building evacuation, few studies have studied specifically the challenges and issues that an actual care facility faces while evacuating its patients. The availability of resources such as staffing, transporting vehicles, and accommodating facilities, are all factors that should be considered when modeling the evacuation scenarios with the main aim of decreasing the total evacuation time, or risk on the patients [3].

Factors that we usually look at when modeling any evacuation scenario as mentioned above are mainly the availability of resources, travel times and risks involved while evacuating. However, other factors to consider when preparing for an evacuation procedure are the weather, the area being evacuated, the type (patients, disabled, or people that can support themselves) and number of evacuees, and finally the type of incident that occurred. Hospitals may need to evacuate their facilities for several possible threats, these threats might be natural or human induced disasters. Some of which are; hurricanes, fires, floods, chemical leaks, bomb threats and loss of functionality. There are two evacuation types, immediate and potential evacuation. Immediate is for threats that hit immediately requiring direct evacuation. While potential evacuation is for the disasters foreseen in the near future, like floods and hurricanes and thus the evacuees can be warned before the start of the evacuation process [8].

Once a hospital decides to evacuate there are three main objectives, minimizing casualties, evacuation time, and costs. The objective in this research paper will be to minimize casualties which is highly correlated to minimizing time. Financial considerations and objectives will not be taken into consideration. In other words, any evacuation plan is subject to resource limitations and budget constraints, however the main purpose of any evacuation plan is to minimize the risk on patients and staff [7].

Although in some regions around the world hospitals are required to come up with an emergency plan and do the appropriate drills; however due to the limited number of scenarios that can actually be mimicked and tested, there is no actual efficient and complete plan that allows hospitals to deal with the vast number of scenarios that can really occur [3]. Hence, there is a dire need for a proper evacuation plan that can be performed under a vast number of scenarios that could take place. That plan can only be suggested by a suitable mathematical and optimization models.

Building a sufficient mathematical and optimization model does not guarantee an actual successful executed evacuation. The two main issues that may compromise the realization of an evacuation plan is the lack of communication, and the human behavior which cannot be accounted for accurately in any mathematical model. First, communication among the different parties involved in an evacuation process, will help create an effective evacuation plan that can cater for people of different needs and abilities [9]. For a plan to be properly executed, the most important aspect is communication amongst the different teams, patients, and all the vital resources while evacuating [9]. Second, one of the most important factors that affect evacuation and is usually overlooked, is human behavior and reaction during a disaster. The staff as well as the patients' reactions during an evacuation usually determine the level of success or failure of an evacuation plan [10]. No matter how much thorough planning is put into the evacuation process, its execution is done by individuals which are controlled by emotions and not by scientific parameters. Hence, their behavior can't be predicted accurately by a model [10]. Thus, since all models ignore the human factor; when picking the medical staff, hospitals must have a full assessment on the capabilities of the individuals they hire, and check if they are capable of handling high levels of stress under tragic circumstances without panicking [10].

Finally, as mentioned earlier the main purpose of a hospital evacuation is to minimize the risk of patients and staff, the two main sources of risk are the threat risk and the transportation risk. The threat risk is the reason behind the evacuation (hurricane, flood, chemical leak…) and inherently the type of threat risk will affect the evacuation plan. Different threat risks are characterized by the different impact on the various types of patients, how this impact will evolve over time, and the number of effected hospitals due to the occurrence of this threat. A chemical leak will only pose a threat on one hospital and not on an area containing several hospitals, while a flood will effect multiple hospitals that will need to be evacuated. A hurricane will not pose a threat immediately since it can be predicted but will pose a high threat as time evolves. And a power outage would pose a huge threat on patients that depend on lifesaving equipment while posing barely any threat on other patients. It is worth mentioning that while in some scenarios partial evacuation is all that is needed, however in the model presented in this paper it is assumed that all patients must evacuate the hospital. This can be amended easily by eliminating the constraint that forces all patients to be evacuated from the hospital, and/or specifying the set of patients that must evacuate.

In short in this research paper the main aim is to devise a mathematical model that will give us the optimal way of evacuating patients from a hospital under a threat. This will require removing the patients from their ward to the staging area [7] (which will most likely impose a bottleneck in reality during the evacuation process), then they will be loaded to their designated vehicles in the loading area. The vehicles will be transporting them to receiving care facilities. All the following will take place while having a main objective which is the minimization of the risk on these patients. This is done while considering the availability of staff in the evacuating hospitals, accessibility to transport vehicles, transport time to the receiving hospitals and the availability of beds in those hospitals along with other factors that will be discussed later in this paper.

CHAPTER 2

LITERATURE REVIEW

In previous years, extensive research has been done on developing evacuation schemes with very limited research done on hospital evacuation. While these two types of evacuation differ tremendously, not only papers related to hospital evacuation was considered, but also papers that deal with building evacuation was revised and studied; and some ideas where used to build the foundation that our model was built on. Thus, the following literature review is a compilation of ideas taken from different papers and how they relate to the model presented in this research paper.

Given recent studies, it was deduced that the newest model developed for evacuation is the dynamic model. The dynamic model is a model that describes the evacuation process as time elapses in discrete consecutive time periods. Some models maximize the number of people evacuated in a single time period and minimize the number of time periods where the last individual evacuates; this is done by minimizing the average time periods needed by each occupant [14]. Other models such as the graphical and intermediate models are easier to use because they are time independent [13]. However, since the dynamic model is time dependent queuing might appear in the model which is more realistic [14]. Dynamic models will use mixed integer programing [15] to produce optimal solutions. Time is discretized into small time intervals (0…T). T may be assigned, depending on the time until the building collapses, or when evacuation is no longer feasible from a given disaster, where all evacuees ideally must be evacuated by time T. The model which will be introduced in the next section is dynamic, with discretized time intervals, the optimal T to be used is found by doing several runs given a certain number of patients. It is better to use an optimal T rather than choosing a large T to decrease the computational/running time of the solver.

Choosing the duration period of a single time interval (5, 10, 15 minutes…) can be tricky sometimes. However, studying the different components within the system will allow us to make a better decision, whether accuracy is more important than faster running time, [14] or vice versa will play a role in choosing the duration of a time interval. Noting that the time where the disaster hits is synchronized to be the time t=0 in any mathematical model [18].

In building evacuation several objectives where taken under consideration, some of which are: First, to find the best way to evacuate a building, the problem can be formulated as a minimization of cost problem, by assigning a cost coefficient to each travel time between the nodes on an arc, thus by minimizing the total cost we would be minimizing the total travel time, and any unnecessary movement is dodged [11]. Using the cost coefficients, we can compare between several alternatives or flows, and decide which path is the best. Arc capacities can be also introduced and can be flow dependent [12]. This can be utilized in the case of hospital evacuation given the time intervals we can compare the better alternative and onto which hospital the patient must be transferred to.

Another way to evacuate a building is by using the concept of preferential evacuation based on the location of the evacuees and the severity of the danger they are exposed too, the evacuees with priority will be evacuated with the objective of evacuating them in the least time possible [11]. After all the preferred evacuees are evacuated; the rest will be evacuated with the least time possible, combining these two times to get the total evacuation time [11]. This is achieved by giving a higher cost coefficient for the evacuees that need to be evacuated first or forcing them to be evacuated first by a constraint [11], and can be generalized to include several priority levels [11]. This can be used in the model presented, by giving a higher threat risk coefficient to patients that are more critical or desired to evacuate first, the model will automatically start evacuating them first if it's possible and overall optimal to do so given all the constraints imposed, in the aim of minimizing the total risk.

Third way is to maximize the number of evacuees within a given number of time intervals. The forth has an objective which is to minimize the number of time intervals until the last evacuee leaves the building [12]. All the above mentioned objective functions serve the higher objective which is evacuating all the people and saving lives. The third approach will require several iterations to realize the number of time intervals required to evacuate everyone and thus assigning this time interval in the objective function. Hence, it's an exhaustive approach unless we only require the evacuation to take place within a certain predetermined number of time intervals.

In the model presented in this paper, a hybrid objective function will be used, where a large number of time intervals is given and the maximum number of evacuees must leave before the end of the last time interval. Approach one is utilized as well where our cost factors are the risk factors (transportation and threat risk factors) associated with each type of patient evacuated and vehicles used to transport the patients from the evacuating hospitals to the receiving ones. Automatically, the patients will be evacuated in the least possible number of time intervals to minimize the total risk. Noting that all patients will be forced to be evacuated with a constraint or by assigning a lower transportation risk values than threat risk values (if they remain in the hospital) which will force the patients to leave the hospital to minimize the total risk. Noting that the increase in the cumulative threat risk on patients as time elapses is enough to force the patients to leave the hospital.

Although an important factor, but the literature does not discuss the different bottlenecks that occurs during an evacuation process [14]. Thus, although our objective is to minimize the risk and thus the evacuation time, however we must do so while taking into consideration the bottlenecks that might occur in our system which will affect the time required for evacuation the most.

The physical characteristics of any facility being evacuated play an important factor during emergencies, sometimes even being a hindering factor during an evacuation process [13]. Newly built facilities must take corridors, doors, rooms, and stairs' physical characteristic during the design phase into serious consideration. Characteristics such as the width which effects the capacity must be tested before hand to check if they handle not only normal circulation, but also the circulation during an emergency [13]. With proper design, bottlenecks can be eliminated or their effect will be to say the least diminished, and the blocking of evacuees which usually occur in most evacuation problems because of capacity (physical) restrictions will be reduced.

Sensitivity analysis regarding these physical characteristics should be performed and would help in determining the design dimensions necessary to provide good conditions for circulation [13] during both normal and emergency times. In the model presented in this paper there will be an assumption which states that all hospitals' corridors, stairs, rooms and doors are designed properly and will not cause any bottlenecks. Thus, we will assume that the time to transport patients of the same type to the staging area will always be fixed throughout the evacuation process. The only physical restriction are vehicle lane capacity in the staging area of the hospital, however the bulk of the restrictions in our model are not due to the physical characteristics of the hospital, but due to the limited resources (limited numbers of teams, cars, beds…).

One paper proposed that coming up with an efficient model necessitates that a plan for the region and the building must be studied [13] where the architectural scheme of a building is transformed into a set of arcs and nodes [12], where arcs (hallways, stairs) connect nodes (offices, rooms) with each other. This will be later on translated into the mathematical model devised for the evacuation problem of the given building [13]. Therefore, in the model presented in this research paper, it is important to plan and analyze the number of time intervals needed to go to the staging area, the number of time intervals between hospitals and the capacity of the lanes in the evacuating hospital which will be used as inputs in the model.

It is also noted that the service rate decays as the occupant traffic increases [13]. This is reflected in our problem in the waiting time of the patients in the staging area given the number of patients already in the staging area. The more patients available in the staging area the more a patient will wait until he/she is transported to the receiving facility. Hence, the first patient will wait less than the fifth patient. Keeping in mind that there is no preference between different patients of the same type it's always a random pick of who will be evacuated first.

In some of the papers reviewed it was assumed that in each floor there exists an independent exit [12]; however in the case of hospital evacuation there exists only one staging area were patients will be loaded to a vehicle which will take them to a receiving hospital. Thus this assumption while insightful, cannot be adopted in our model. Other papers proposed an algorithm where the building in the model would be transformed into a tree structured network, where corridors are branches heading to a root which is a one exit node [12], meaning all the nodes will be directed towards one exit. The network structure in the model being proposed in this paper is the other way around, for the case of one hospital being evacuated it will be a root node diverging to several nodes which are, the receiving hospitals. As for the case of multiple hospital evacuation the network will have several root nodes with branches that stem to several nodes. Where in both cases we will be only considering that the number of time intervals needed till the patient leaves his/her ward to the staging area in the hospital depends on the type of patient being evacuated. Neglecting the different paths and the optimal one that could be taken to evacuate the hospital internally, since otherwise the model will be too complicated to formulate and solve.

Physical characteristics of a building can also be used to aid in the evacuation process, by utilizing the available building's map for the arcs (hallways) travel times and their capacities, which will vary over time [15]. Using this information in a mixed linear program, evacuees will receive live instructions [15] on which route must be taken to reach safety and which routes are no longer viable for usage. Thus, eliminating the common hinders during an evacuation, such as taking a wrong route or having congestion within the safest route [15], keeping in mind that any feasible solution shouldn't contain more than one path from a certain location (node), to abolish any chaos and confusion among evacuees [15] by providing common instructions. This is done via online, voice systems, luminous signage or by messages. The instructions to each evacuee are dependent on his/her location insuring that evacuees within the same location will receive common instructions [15]. This can be applied on any building undergoing a natural or human induced disaster which imposes threat on the occupants of the building, suffice that the evacuees are fully capable to aid themselves during the evacuation process. As mentioned earlier in the model presented in this research paper, we don't specify travel times in each arc within the hospital but impose a general travel time for evacuating each patient depending on the location of the ward in the hospital for this type of patient; since for simplification, we are assuming that the staff will be taking the same route to aid the patients and transport them from their ward to the staging area. Moreover, such practices (online, voice systems, luminous signage or messages) can be suggested and used in real life while evacuating hospitals, which will decrease the real time needed for the staff to transport the patients to the staging area.

Finally, in previous studies the main focus was maximizing the utilization of existing buildings and transportation networks during an evacuation process given that the cost of increasing the existing capacity is very high and out of the question [19]. However, nowadays studies have been oriented towards analyzing the results and time needed for an evacuation, which may give us insight on some adjustments that need to be made regarding the design of a facility before building it, and if it is already built then the redesign of such a facility to insure a better evacuation [14]. Knowing where will queuing take place might allow us to enhance the evacuation process and decrease the queuing. For example, if in a hospital the major delay is due to the number of lanes that the vehicles are allowed to use while loading the patients, the hospital might consider constructing new lanes. Building designers, insurance company, management of the facility and public safety officials are all potential responsible parties in case of an occurrence of an accident during an evacuation [14], this liability on the aforementioned parties should make it a priority to study the bottlenecks to try enhancing any existing emergency plan.

Some questions that might be assessed for all buildings including hospitals [14]:

- Assuming a fire occurs, or a chemical leak occurs on a high floor how should the building be evacuated (which floors first)?
- Should elevators be used or only staircases?
- What if the staircases are on or blocked by fire, or exposed directly to the fire/chemical leak?
- Should we add more exits?

- Should we add more stairwells?

When a disaster occurs on a big scale, it will force a whole area to be evacuated and not just the hospital alone, causing a contact between the former and the latter. Research papers and models, often neglect and don't have any sufficient information about the interaction between care facilities' evacuation and the evacuation of the general population of the area under threat [16]. By taking deterministic travel times, the effect of real life variability of the travel times is neglected. During an evacuation process there will be more congestion than in normal circumstances since we will have a necessary simultaneous evacuation [15]. Thus, to account for the variability of the capacities in each traveling arc in the network [12] it is more realistic to take the traveling times as stochastic times [16] that depend on the capacity and accordingly the flow of vehicles [7] on the roads during the disaster. Another method proposes an integer programing order to compute the optimal routing plan that should be taken by the vehicles during an evacuation [17]. An M/G/c/c queuing model is utilized to calculate the travel times along the links [17].

In the model presented in this research paper, deterministic travel times will be taken by assuming a fixed travel times between the different care facilities throughout the evacuation procedure. This assumption is taken to simplify the problem in hand, since to estimate the change in travel times of each route between the evacuating and receiving hospitals, we need to specify an area and hospitals to study and to know the different O-D pairs we may use several flow to speed equations or a relation with density [16]. Then getting such a relationship using any of the known relationships and equations we might be able to get a variation of the travel time as time passes. Moreover, upon taking the travel times to be stochastic instead of deterministic, it will be harder to track an optimization problem [3]. Hence, approaching our problem by using deterministic travel times, although gives an approximate solution but is more tractable.

Evacuee behavior was studied in many papers. It was shown that during an evacuation there is a sense of collective behavior, people tend to follow each other and look for clues on what decision to take and ultimately there will be a natural leader in action [15], moreover they will seek to be reunited if separated during an evacuation [15], a concept known as un-split able flow [17]. Furthermore, given the human nature once a disaster hits, the individual will prefer the apparent safest path (which will cause congestion on that path) not the path that will realistically be the safest with the minimum time. Neither any of the previously devised models in the literature, nor the model discussed in this research paper captures the variation due to the natural randomness in the human behavior, since it cannot be measured accurately.

When an evacuation model is devised, one of the main objectives is to check whether a building can be evacuated in an acceptable time. Checking performance measures will aid us when devising such a model, as well as identify if an equation must be revised, updated or added. Local and empirical practices were what traditional evacuation plans depended on previously. However, with the booming of the operations research sector many studies have been issued with a clear objective of optimizing the evacuation process. With the increase of such research papers, establishing a well-defined set of measures of effectiveness are crucial to evaluate the effectiveness and benefits of each optimization process if implemented.

The time required for all evacuees to evacuate on time is called the network clearance time and it is the most important measure of effectiveness [19]. Different processes can have the same clearance time but different efficiencies [19], thus some studies measure the clearance time for a certain percentage of the population and compare these times; this is used as a measure of effectiveness [19]. Another method is to use risk coefficients as weights with time to develop more effective strategies, and using the utilization of resources as another measure of effectiveness [20].

CHAPTER 3

MODEL

The model which will be introduced in this section is dynamic, with discretized time intervals, the optimal T is found by doing several runs given a certain number of patients. It is better to use an optimal T rather than choosing a large T to decrease the computational/running time of the solver.

First, the total delay and the exposure to threat during evacuation are two important criteria that must be considered. In our problem it is reflected by the risk coefficients and how they are increasing with time as the patient is exposed to the disaster. Threat risk increases with time because as time increases the cumulative risk on the patient are bound to increase. Even when a disaster hits which causes a higher immediate threat, causing the instantaneous threat risk to decrease as time increases; however there will always be added threat in each time interval which will mean an increase in the cumulative threat risk as the time intervals increase.

The evacuation model developed, aims to minimize both the transportation and threat risk of the patients. In this model hospital's patients will be assisted by the staff to the staging area, then outside the building, where they will be transported via vehicles to other hospitals. Thus the evacuation of the hospital is dependent on the transportation of the patients to other receiving hospitals. Evacuation of patients is ordered, patients in the staging area will definitely evacuate faster than the patients that belong to the same type and are still in their wards. In other words, the model assumes FIFO (first in the staging area first out or evacuated) within the same type of patients. The travel times until the patient reaches the staging area must be defined based on previous experience within the hospital under study, given their corridors and the location of each ward for each type of patient. In addition:

- There is no preferential treatment between the patients of the same type, there is no preference to who will be taken first to the staging area. However, for different types of patients having different risk coefficients there will be preferential treatment by evacuating the more critical patients to minimize the total cumulative risk.
- Patients in private clinics will not be accounted for, as they are not admitted in the hospital and should not need special assistance.
- The evacuation teams are considered to be made up of specialized medics and nurses.

The figure below depicts the complete evacuation process.

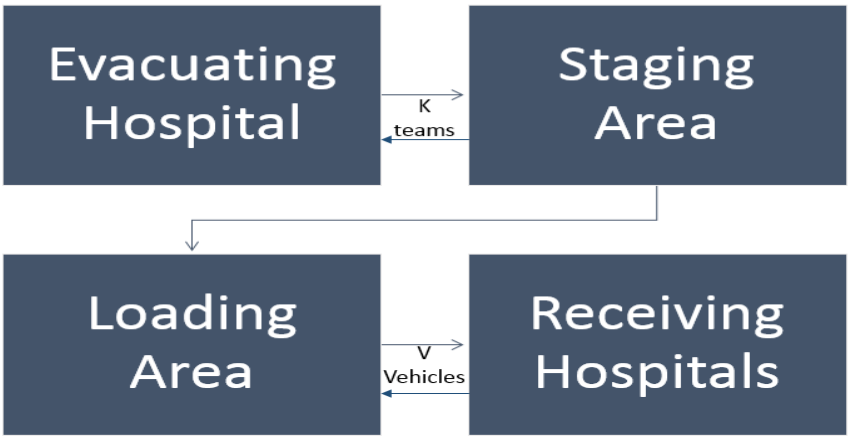


Figure 2: The evacuation process

3.1. Single Hospital Evacuation

The evacuation of a hospital can be taken as a process that is made up of two phases. The first phase of a hospital evacuation is the process of moving patients from their location in the hospital to the staging area. The second phase is the process of loading the patients into an ambulances/vehicle and transporting them to the receiving hospitals. The proposed model, which is the evacuation of a patients in a single hospital to several receiving hospitals can be easily expanded to include multiple synchronized evacuating hospitals as is proposed in section 3.2., the resulting model is an integer program, in which the structure is complex.

3.1.1. Assumptions

The following are assumptions taken in the model with the aim of decreasing an already complex model. These assumptions were set carefully and cautiously as to maintain a realistic model that mimics a real life evacuation scenario.

1- Vehicles do not stop at multiple receiving hospitals.
2- Loading time of a vehicle is independent of the patient type in it.
3- Loading time and unloading time of a vehicle are equal.
4- Travel times to receiving hospitals have known fixed lengths depending on the location of the receiving hospitals and the evacuating hospital. And doesn’t depend on the vehicle type in the model.
5- Each patient type is assigned to a corresponding bed type in the receiving hospitals.

6- Time to move a patients from his/her ward to the staging area is only dependent on the patient type, and location of the ward for this type of patient in the hospital.
7- The transportation risk is related to the travel, loading and unloading time.
8- All evacuation teams are assumed to be at the staging area at the beginning of the planning horizon and a team is assumed to move one patient at a time.
9- The travel time from the evacuating hospital to a receiving hospital is assumed to be equal to the travel time of the journey from the receiving hospital back to the hospital being evacuated.

3.1.2. The Model's Parameters

In our problem we have five main components that are intertwined with one another: Patients (P), Vehicles (V), Hospitals (H), Lanes (L), Evacuation teams (K), as well as other sub-components.

❖ Parameters of the model:

- P is the set of patients of type p, such that $p \in P$.
- $W_p$is the initial total number of patients of type p in the evacuating hospital, such that $p \epsilon P. W = \sum_p W_p$, is the total number of patients to be evacuated.
- H is the set of all hospitals, which include both the receiving hospitals and the hospital being evacuated.
- J is the set of all potential receiving hospitals j, such that $j \in J$.

- B is the set of types of beds b in each hospital, thus B_b^j symbolizes the number of beds of type b in hospital j. Where each type of bed b would accommodate a subset of patients P, meaning it would accommodate one or more patient types.
- Example: $b_1 \rightarrow [p_1, p_3, p_4]$ (bed type one can accommodate patients of type one, three and four)
- The set of patients that would be accommodated by a bed of type b is donated by P_b, such that $P_b \subset P$. Using the previous example $P_{b_1} = \{p_1, p_3, p_4\}$.
- T is the total number of time intervals of a study period divided into time intervals t of equal lengths.
- K is the set of types of evacuation teams k, categorized based on their capabilities, i.e. the type of patients they can transport to the staging area. Such that $\in K$.
- The set of teams that can assist patients of type p is denoted by K_p, such that $K_p \subset K$.
- M_k^t is the total number of available evacuation teams of type $k \in K$ at time t.
- The number of time intervals to transfer the patient of type $p \in P$ from his ward to the staging area is, τ_p time intervals.
- V is the set of vehicle types v, such that $v \in V$.
- N_v^t is the total number of vehicles $v \in V$, at time t.

- The loading time of a vehicle of type v is γ_v time intervals, which is assumed to be equal to the unloading time of the vehicle.
- τ^j is the number of time intervals required to travel from the evacuating hospital to receiving hospital $j \in J$, which is assumed to be equal to the journey back from the receiving hospital j to the evacuating hospital.
- Q_v denotes the maximum capacity of a vehicle $v \in V$.
- $C_{p_i v}$ denotes the total number of patients of a specific type p_i that can be loaded onto a vehicle of type $v \in V$, for a given set of patients $P_i \subset P$, where P_i is the set of patients $p_i \in P_i$ that can be loaded onto this type of vehicle $v \in V$.
- $C_v = \sum_{p_i \in P_i} C_{p_i v}$ is the total number of patients that can be loaded onto a vehicle of type $v \in V$.
- L is total number of lanes in the hospital being evacuated.

The evacuating hospital's loading area imposes a limitation on the number of vehicles that can load patients simultaneously at a certain time interval. This is represented by a set of parameters, L_{v_i} which represents the total number of lanes available for a given set of vehicles $v_i \subset V$, Where v_i represents the set of types of vehicles allowed on lane L_{v_i}.

3.1.3. Threat Risk and Transportation Risk

The objective of the model is to minimize the overall cumulative threat and transportation risks of all patients being evacuated from the hospital within T time intervals and limited resources.

3.1.3.1. Threat Risk

The threat risk is created due to the impact of the disaster on the various patient types and how that disaster evolves over time. It is the instantaneous probability of the undesired event for a patient of type $p \in P$ that remains in the evacuating hospital at time interval t. It will take a value between 0 and 1 in each time interval. It is the risk that will push all the patients to evacuate, since the cumulative risk will always increase as time increase.

- λ_{pt} is the probability of the undesired event for a patient of type p that remains in the hospital at time t. Each λ_{pt} is assumed to be independent from any other instantaneous probability in any other time interval.
- The cumulative threat risk $\Lambda_{\boldsymbol{pt}}$ is calculated in the equation below.

$$\Lambda_{pt} = 1 - \prod_{f=1}^{t}(1 - \lambda_{pt}) \quad \forall\ p \in P, t = 1,2, \ldots T \tag{1}$$

3.1.3.2. Transportation Risk

Transportation risks arise when the patients are being loaded into the vehicle, transported to alternative hospitals or care facilities, as well as when being unloaded into these facilities. The transportation risk is an instantaneous probability taking a value between 0 and 1, it is a function of the patient type, the vehicle, and the time required to transport the patient to the selected receiving hospital. Certain patients might be safer if evacuated whereas other might not tolerate the transportation risk, however we assume in our model that everyone is better off being evacuated.

- θ_{pv} denotes the probability of the undesired event for a patient of type $p \in P$ transferred by a vehicle of type $v \in V$ for one time interval t.
- Θ_{pv}^{j} represents cumulative transportation risk for a patient of type $p \in P$ transferred by a vehicle of type $v \in V$ to hospital $j \in J$.

A vehicle $\boldsymbol{v}$ transporting a patient to hospital j, would have a total time of loading, unloading, and travel time to go from and to the evacuating hospital *of* $[2(\tau^{j} + \gamma_{v})]$ time units , where τ^{j} is assumed to be dependent on the destination and not the vehicle. However; $(\tau^{j} + 2\gamma_{v})$ is the only time accounted for, since the transportation risk could only be incurred when a patient is found in the vehicle, hence when the vehicle is returning back there is no risk imposed on any patient, thus one $\boldsymbol{\tau^{j}}$ time units will be excluded while calculating the threat risk.

- The cumulative transportation risk Θ_{pv}^{j} is calculated in the equation below.

$$\Theta_{pv}^{j} = 1 - (1 - \theta_{pv})^{(\tau^{j} + 2\gamma_{v})} \quad \forall\, j \in J, p \in P\,, v \in V, t = 1,2 \ldots T \qquad (2)$$

The evacuation risk of a patient is the sum of the cumulative threat and transportation risk imposed on this patient.

3.1.4. Decision Variable

- $\boldsymbol{S_{pkt}}$: Number of patients of type p moved from their ward in the evacuating hospital to the hospital's staging area by a team of type k in time interval t, $\forall\ p \in P\,, k \in K,$ and $t = 1,2, \ldots T$

- $\boldsymbol{x^{j}_{pvt}}$: Number of patients of type p transported from the staging area of the evacuating hospital to the staging area of receiving hospital j by a vehicle of type v in time interval $t, \forall\, p \in P,\ v \in V, j \in J$ and $t = 1,2, \ldots T$
- $\boldsymbol{y^{j}_{vt}}$: Number of vehicles of type v that move to hospital j at time interval $t, \forall\, j \in J, v \in V,$ and $t = 1,2, \ldots T$

3.1.5. The Mathematical Model

3.1.5.1. Objective Function

The objective function minimizes the total evacuation risk where the summation represents the total risk on patients evacuated from the hospital, and transported to alternative care facilities.

- Objective Function:

Minimize $Z =$

$$\sum_{j \in J} \sum_{p \in P} \sum_{v \in V} \sum_{t=1}^{T} \Theta^{j}_{pv}\, x^{j}_{pvt} + \sum_{p \in P} \sum_{t=1}^{T} \Lambda_{pt} \left(W_p - \sum_{j \in J} \sum_{v \in V} \sum_{i=1}^{t} x^{j}_{pvt}\right) \qquad (3)$$

3.1.5.2. Constraints

- Transportation Teams Constraints:
  - **Constraint 1**: Sets the restriction of upgrade team assignment strategy. No patients are transported by teams that are not specialized in transporting patients of type $p \in P$

$$\sum_{t=1}^{T} S_{pkt} = 0 \quad \forall \; p \in P, k \notin K_p \tag{4}$$

- **Constraint 2**: Teams available to transport patients of type $p \in P$, should be restricted by the maximum total number of teams available of type $k \in K$ at time t.

$$\sum_{p \in P} \sum_{f=0}^{min(\tau_p - 1, t-1)} S_{pk(t-f)} \leq M_{kt} \quad \forall \; k \in K, t = 1,2, \dots T \tag{5}$$

- Patients Constraint:
    - **Constraint 3**: The total number of patients that can be moved to the staging area is limited by the initial total number of patients W_p.

$$\sum_{k \in K} \sum_{t=1}^{T} S_{pkt} \; \leq \; W_p \quad \forall \; p \in P \tag{6}$$

- **Constraint 4**: The number of patients to be transported from the loading area to the corresponding hospitals, cannot be more than the actual number of patients available at the staging area at time t.

$$\sum_{k \in K} \sum_{f=1}^{t-\tau_p : t > \tau_p} S_{pkf} - \sum_{j \in J} \sum_{v \in V} \sum_{f=1}^{t} x_{pvf}^{j} \geq 0 \quad \forall \; p \in P, t = 1,2, \dots T \tag{7}$$

- Bed Capacity Constraint:
    - **Constraint 5**: Limits the total number of patients of type $p \in P_b$, transported in vehicle $v \in V$ throughout all the evacuation procedure; to the number of available beds that can accommodate these types of patients, in each receiving care facility.

$$\sum_{v \in V} \sum_{p \in P_b} \sum_{t=1}^{T} x_{pvt}^{j} \leq B_b^j \quad P_b \subset P, \forall\, j \in J, and\ b \in B \tag{8}$$

- Vehicle Capacity Constraint:
    - **Constraint 6**: Represents the vehicle capacity restriction on the total number of patients that can be transferred at each time interval, since each vehicle can fit a maximum fixed amount of patients at a time.

$$\sum_{p \in P_v} x_{pvt}^{j} \leq C_v y_{vt}^{j} \quad \forall\ j \in J, v \in V, P_v \subset P, and\ t = 1,2, \dots T \tag{9}$$

- Vehicle Type Constraint:
    - **Constraint 7**: Restricts the patients from being transferred in vehicles they can't be transported on, since different vehicles can accommodate different types of patients and their respective needs.

$$\sum_{p \notin P_v} x_{pvt}^{j} = 0 \quad \forall\ j \in J, v \in V, P_v \subset P, t = 1,2, \dots T \tag{10}$$

- Vehicle Fleet Size Constraint:

  - **Constraint 8**: Bounds the number of busy and idle vehicles by the total number of vehicle available in each time interval t.

$$\sum_{j\in J} y_{vt}^{j} + \sum_{j\in J}\sum_{n=t-2\tau^{j}}^{t} y_{vn}^{j} \leq N_{v}^{t} \quad \forall\ v \in V, t = 1,2, \dots T \tag{11}$$

- Physical Loading Capacity Constraint:

  - **Constraint 9**: Restricts the total number of vehicles that can load patients in their designated lanes at each time interval t, to the total number of lanes L_{v_i} that can accommodate these different vehicle types. This is a physical loading capacity constraint.

$$\sum_{j\in J}\sum_{v\in V_i}\sum_{f=t-\gamma_v+1}^{t} y_{vf}^{j} \leq L_{v_i} \quad V_i \subset V, \forall\ t = 1,2, \dots T \tag{12}$$

- Evacuation Constraint:

  - **Constraint 10**: Insures that every patient is evacuated, since the code is mathematical and the minimization objective might lead to achieving the minimum risk by not evacuating any patient at the end of time T (if the threat risk is much lower than the transportation risk), or if the time intervals are not sufficient to evacuate all patients, some patients might be left in the hospital at the end of time T. Thus, this constraint will force the patients to be evacuated. By giving an infeasible solution while solving the model it can be inferred that the number of time intervals T is not sufficient.

$$\sum_{j\in J}\sum_{v\in V}\sum_{t\in T} x_{pvt}^{j} \quad = W_p \tag{13}$$

- Constraints 11-13 are the integrality and non-negativity constraints.

  - **Constraint 11:**

$$S_{pkt} \ \geq 0 \ \text{ and integer } \ \forall \ p \in P, k \in K, t = 1,2, \dots T \tag{14}$$

  - **Constraint 12:**

$$x_{pvt}^{j} \geq 0 \text{ and integer } \ \forall \ p \in P, v \in V, j \in J, t = 1,2, \dots T \tag{15}$$

  - **Constraint 13:**

$$y_{vt}^{j} \geq 0 \text{ and integer } \ \forall \ v \in V, t = 1,2, \dots T \tag{16}$$

3.2. Multiple Hospital Evacuation Model

The evacuation model developed, aims to minimize both the transportation and threat risk of the patients being evacuated from two or more hospitals that are typically located within the same area. This area is under the impact of a certain natural or human induced disaster and thus taking several synchronized hospital evacuation instead of one hospital will give our model a better and much needed realistic results.

The results will mimic real life situations better than when studying one hospital being evacuated at a time, the reason behind this lies within the resources themselves. When a disaster hits a certain region, all the hospitals in that region will be forced to evacuate sharing resources in the process, hence by studying one hospital alone our model will assume that all of the available resources will be used on this hospital which is an illogical assumption and will not give us accurate results.

Having said that, the model that considers the evacuation of one hospital will not be abandoned, it shall be utilized for hospitals that lie in regions on their own such as in rural areas where hospitals are rare and far apart from one another. This model can also be used for hospitals that hold their own fleet of vehicles and other resources, making it a safer hospital during an evacuation since it will not share any resources and will incur less delays affected from the sharing of resources during the evacuation process. Finally, it can also be used when a disaster limited to one hospital hits, such as chemical leaks, bomb threats or loss of functionality.

The resources that will be shared during an evacuation will typically be the evacuating vehicles, and beds in receiving hospitals. As mentioned earlier, in this model the hospital's patients will be assisted by the staff from their wards to the staging area, where they will be transported via vehicles to other receiving hospitals. Thus the evacuation of the hospital is dependent on the transportation of the patients to other receiving hospitals, and not leaving the hospital premises but insuring the safety of the patients by insuring that they are safely institutionalized in a hospital located outside the danger zone.

As with the model that deals with the evacuation of one hospital, in this model the resulting model is an integer program, in which the structure is complex.

The evacuation of any hospital in the model can be taken as a process that is made up of two phases. The first phase of a hospital evacuation is the process of moving patients from their location in the hospital to the staging area. The second phase is the process of loading the patients into an ambulances/vehicle and transporting them to the receiving hospitals. The decision variables in the previously introduced model, was modified to include an index that specifies evacuating hospitals. By that we are able to keep track of each vehicle and patient type leaving each evacuating hospital to each receiving one. We will also be able to track the vehicles leaving the receiving hospitals to each evacuating hospital.

Unlike in the case of one hospital being evacuated, it is essential to keep track of all the vehicles leaving each evacuating/receiving hospital. We can't evacuate a patient without having a vehicle ready in the loading area, and thus we need to know which vehicles are leaving each receiving hospital back to which evacuating hospital, by that knowing in the subsequent time intervals what vehicles are found in the evacuating hospitals ready to load patients. To achieve this we will introduce a new decision variable that is much similar to the decision variable which indicates the number of vehicles leaving each evacuating hospital to each receiving one; however it will be giving us the number of vehicles leaving each receiving hospital back to each evacuating hospital. By that we can know the status of each vehicle in the model whether it is in the loading/unloading area or on the road from/to the evacuating/receiving hospitals.

3.2.1. Assumptions:

The following are assumptions taken in the model with the aim of decreasing an already complex model. These assumptions were set carefully and cautiously as to maintain a realistic model that mimics a real life evacuation scenario.

1- Vehicles do not stop at multiple receiving/evacuating hospitals. Evacuating hospitals will share the vehicles as a shared resource.
2- Loading time of a vehicle is independent of the patient type being loaded.
3- Loading time and unloading time of a vehicle are equal, however differs for different vehicle types.
4- Travel times to receiving hospitals from each evacuating hospital have known fixed lengths, depending on the locations of the different evacuating and receiving hospitals. And does not depend on the vehicle type in the model.
5- Each patient type should be assigned to the corresponding bed type suitable for its type.
6- Time to move a patients from his/her ward to the staging area is only dependent on the patient type.
7- The transportation risk is related to the travel, loading and unloading time.

8- All evacuation teams are assumed to be at the staging area at the beginning of the planning horizon and a team is assumed to move one patient at a time.

9- The travel time from the evacuating hospital to a receiving hospital is assumed to be equal to the travel time from the receiving back to the evacuating hospital.

3.2.2. The Model's Parameters

In our problem we have five main components that are intertwined with one another: Patients (P), Vehicles (V), Hospitals (H), Lanes (L), Evacuation teams (K), as well as other sub-components.

❖ Parameters of the model:

- H is the set of all hospitals which include both receiving and evacuating hospitals h, such that $h \in H$.
- J is the set of potential receiving hospitals j, such that $j \in J$.
- E is the set of evacuating hospitals e, such that $e \in E$.
    - Thus $H = \{\mathrm{J} + \mathrm{E}\}$
- P is the set of all patients type p**,** such that $p \in P$**.**
- P_e is the set of patients of type p in hospital e, such that $p \in P$, $e \in E$.
- W_{pe} is the initial total number of patients of type p, where $p \epsilon P$ in the evacuating hospital e, Where $e \in E$.

- $W = \sum_e \sum_p W_{pe}$,is the total number of patients to be evacuated from each hospital $e \in E$.
- B is the set of types of beds b in each hospital, thus B_b^j symbolizes the number of beds of type b in hospital j. Where each type of bed b would accommodate a subset of P, meaning it would accommodate one or more patient types.

  Example: $b_1 \rightarrow [p_1, p_3, p_4]$ (bed type one can accommodate patients of type one, three and four)
- The set of patients that would be accommodated by a bed of type $b \in B$ is donated by P_b, such that $P_b \subset P$. Using the previous example $P_{b_1} = \{p_1, p_3, p_4\}$.
- T is the total number of time intervals in the study period divided into time intervals t of equal lengths.
- K is the set of types of evacuation teams k, categorized based on their capabilities, i.e. the type of patients they can transport to the staging area. Such that $\in K$.
- K_e is the set of evacuation teams available in hospital e .
- The set of teams in hospital e that can assist patients of type p is denoted by K_{ep}, such that $K_{ep} \subset K_e$.
- M_{ek}^t is the total number of available evacuation teams in hospital e of type $k \in K_e$ at time t .
- The number of time intervals to transfer the patient of type $p \in P$ in hospital $e \in E$ from his/her ward to the staging area is τ_{pe} time intervals.

- V is the set of vehicle types v, such that $v \in V$.
- N_v^t is the total number of available vehicles $v \in V$ at time t.
- N_{ve}^t is the total number of available vehicles $v \in V$, in hospital $e \in E$, at time t.
- The loading time of a vehicle of type v is γ_v, which is assumed to be equal to the unloading time.
- τ^{ej} is the number of time intervals required to travel from the evacuating hospital $e \in E$ to receiving hospital $j \in J$, which is assumed to be equal to the journey back from hospital j to hospital e.
- Q_v denotes the maximum capacity of a vehicle $v \in V$.
- $C_{p_i v}$ denotes the total number of patients of a specific type p_i that can be loaded onto a vehicle of type $v \in V$, for a given set of patients $P_i \subset P$, where P_i is the set of patients $p_i \in P_i$ that can be loaded onto this type of vehicle $v \in V$.
- $C_v = \sum_{p_i \in P_i} C_{p_i v}$ is the total number of patients that can be loaded onto a vehicle of type $v \in V$, Such that $C_v \leq Q_v$.
- L_e is total number of lanes in hospital $e \in E$.

The evacuating hospital's loading area impose a limitation on the number of vehicles that can load patients simultaneously at a certain time interval. This is represented by a set of parameters L_{ev_i} which represent the total number of lanes available for a given set of vehicles $v_i, v_i \subset V$ in hospital $e \in E$. Where v_i represents the set of types of vehicles allowed on lane L_{ev_i}.

3.2.3. Threat Risk and Transportation Risk

The objective of the model is to minimize the overall cumulative threat and transportation risks of all patients being evacuated from the hospitals within T time intervals and limited resources.

3.2.3.1. Threat Risk

Similar to the first model presented, λ_{ept} is the probability of the undesired event for a patient of type $p \in P$ that remains in hospital $e \in E$, at time t. Each λ_{ept} is assumed to be independent from any other instantaneous probability in any other time interval.

The cumulative threat risk Λ_{ept} calculated in the below equation is the probability of the undesired event for a patient of type $p \in P$ that remains in the evacuating hospital $e \in E$ through time interval t.

$$\Lambda_{ept} = 1 - \prod_{f=1}^{t} \left(1 - \lambda_{ept}\right), \quad \forall_p \in P \;, \forall_e \in E, t = 1,2, \dots T \qquad (17)$$

3.2.3.2. Transportation Risk

Similar to the first model presented, θ_{pv} denotes the probability of the undesired event for a patient of type $p \in P$ transferred by a vehicle of type $v \in V$ for one time interval. Θ_{pv}^{j} represents cumulative transportation risk for a patient of type $p \in P$ transferred by a vehicle of type $v \in V$ to hospital $j \in J$.

A vehicle v transporting a patient to hospital j, would have a total time of loading, unloading and travel time, to go from and to an evacuating hospital e, of $2(\tau^{ej} + \gamma_v)$ time units. Where τ^{ej} is taken assuming it depends solely on the origin/destination and not the vehicle type. However; $(\tau^{ej} + 2\gamma_v)$ is the only time accounted for, since the transportation risk could only be incurred when a patient is found in the vehicle, meaning while the vehicle is returning back to an evacuating hospital there is no risk imposed on any patient, thus one τ^{ej} time units will be excluded while calculating the threat risk.

- The cumulative transportation risk Θ_{pv}^{j} is calculated in the equation below.

$$\Theta_{pv}^{j} = 1 - (1 - \theta_{pv})^{(\tau^{j} + 2\gamma_v)}, \forall\, j \in J, p \in P, v \in V, t = 1,2 \ldots T \qquad (18)$$

The evacuation risk of a patient is the sum of the cumulative threat and transportation risk imposed on this patient.

3.2.4. Decision Variables

- $\boldsymbol{S_{epkt}}$: Number of patients of type p moved from their ward in the evacuating hospital $\boldsymbol{e}$ to the hospital's staging area by a team of type k in time interval t, $\forall\, p \in P, k \in K, e \in E, t=1,2,\ldots T$
- $\boldsymbol{x_{epvt}^{j}}$: Number of patients of type p transported from the staging area of the evacuating hospital e, to the staging area of receiving hospital j by a vehicle of type v in time interval t, $\forall\, v \in V\; e \in E, p \in P, j \in J$, t=1,2,...$T$

- $\boldsymbol{y^{j}_{evt}}$: Number of vehicles of type v that move to hospital j from hospital e starting at time interval $t, \forall\, j \in J, v \in V, e \in E, t = 1,2, \dots T$
- $\boldsymbol{y^{e}_{jvt}}$: Number of vehicles of type v that move to hospital e from hospital j starting at time interval $t, \forall\, j \in J, v \in V, e \in E, t = 1,2, \dots T$

3.2.5. The Mathematical Model:

3.2.5.1. Objective Function

The objective function minimizes the total evacuation risk where the summation represents the total risk on patients evacuated from all the hospitals under threat, and transported to alternative facilities.

- Objective Function:

Minimize $Z =$

$$\sum_{e\in E}\sum_{j\in J}\sum_{p\in P}\sum_{v\in V}\sum_{t=1}^{T}\Theta^{j}_{pv}\, x^{j}_{epvt} + \sum_{e\in E}\sum_{p\in P}\sum_{t=1}^{T}\Lambda_{ept}\Big(W_{ep} - \sum_{j\in J}\sum_{v\in V}\sum_{i=1}^{t} x^{j}_{epvt}\Big) \qquad (19)$$

3.2.5.2. Constraints

- Transportation Teams Constraints:
  - **Constraint 1**: Sets the restriction of upgrade team assignment strategy. No patients are transported by teams that are not specialized in transporting patients of type $p \in P$ in hospital $e \in E$.

$$\sum_{t=1}^{T} S_{epkt} = 0 \quad \forall\, p \in P, e \in E, k \notin K_p \;\; for\ each\ e \in E \qquad (20)$$

- **Constraint 2:** Teams available in hospital $e \in E$ to transport patients of type $p \in P$, should be restricted by the maximum total number of teams available of type $k \in K_e$ at time t in each hospital $e \in E$.

$$\sum_{p \in P} \sum_{f=0}^{min(\tau_p - 1, t-1)} S_{epk(t-f)} \leq M_{ek}^{t} \quad \forall\, e \in E, k \in Ke\,, \qquad t = 1,2, \dots T \qquad (21)$$

▪ Patients Constraint:

- **Constraint 3:** The total number of patients that can be moved to the staging area is limited by the initial total number of patients in each hospital e.

$$\sum_{k \in K} \sum_{t=1}^{T} S_{epkt} \leq W_{ep} \quad \forall\, p \in P\,, e \in E \qquad (22)$$

- **Constraint 4**: The number of patients to be transported from the staging area from each evacuating hospital e, to the corresponding receiving hospitals cannot be more than the actual number of patients available at the staging area at time t.

$$\sum_{k \in K} \sum_{f=1}^{t-\tau_{pe}:t>\tau_{pe}} S_{epkf} - \sum_{j \in J} \sum_{v \in V} \sum_{f=1}^{t} x_{epvf}^{j} \geq 0 \quad \forall\, p \in P, e \in E, t = 1,2, \dots T \qquad (23)$$

- Bed Capacity Constraint:
  - **Constraint 5:** Limits the total number of patients of type $p \in P_b$, transported in vehicle $v \in V$ throughout all the evacuation procedure; to the number of available beds that can accommodate these types of patients, in each receiving care facility.

$$\sum_{e \in E} \sum_{v \in V} \sum_{p \in P_b} \sum_{t=1}^{T} x_{epvt}^{j} \leq B_b^j \quad p \in P_b \subset P, \forall j \in J, b \in B \tag{24}$$

- Vehicle Capacity constraint:
  - **Constraint 6:** Represents the vehicle capacity restriction on the total number of patients that can be transferred at each time interval, since each vehicle can fit a maximum fixed amount of patients at a time.

$$\sum_{p \in P_v} x_{epvt}^{j} \leq C_v y_{evt}^{j} \quad \forall j \in J, v \in V, P_v \subset P, e \in E, t = 1,2, \ldots T \tag{25}$$

- Vehicle Type Constraint:
  - **Constraint 7:** Restricts the patients from being transferred in the vehicle they are not allowed to be transported on.

$$\sum_{p \notin P_v} x_{epvt}^{j} = 0 \; \forall_j \in J, v \in V, P_v \subset P, e \in E, t = 1,2, \ldots T \tag{26}$$

- Physical Loading Capacity Constraint:
  - **Constraint 8:** Restricts the total number of vehicles that can load patients in their designated lanes at each time interval t, to the total number of lanes

L_{ev_i} that can accommodate these different vehicle types. This is a physical loading capacity constraint.

$$\sum_{j \in J} \sum_{v \in V_i} \sum_{f=t-\gamma_v+1}^{t} y_{evf}^{j} \leq L_{ev_i}, V_i \subset V, \forall\, e \in E, t = 1,2, \dots T \qquad (27)$$

***Note: we need to keep track of the number of vehicles found in each hospital at each time interval. This is achieved by using the decision variables y_{evt}^{j} and y_{jvt}^{e}.

- Let z_{jv}^{t} be the number of vehicles of type v found or are on their way to the receiving hospital j at time t

  z_{jv}^{t}=inflow-outflow=

$$\sum_{e} \sum_{t'=1}^{t-\tau^{ej}-2\gamma_v} y_{evt'}^{j} - \sum_{e} \sum_{t'=1}^{t-1} y_{jvt'}^{e} \;\; \forall\, j, v, t = 1 \dots T \; and \; t' > 0 \qquad (28)$$

- Similarly, let z_{ev}^{t} be the number of vehicles of type v found in or are on their way to evacuating hospital e at time t

  z_{ev}^{t}=inflow-outflow=

$$\sum_{j} \sum_{t'=1}^{t-\tau^{ej}-2\gamma_v} y_{jvt'}^{e} - \sum_{j} \sum_{t'=1}^{t-1} y_{evt'}^{j} \;\; \forall e, v, t = 1 \dots T \; and \; t' > 0 \qquad (29)$$

- Physical Loading Capacity Constraint:
  - **Constraint 9**: Bounds the number of busy and idle vehicles by the total number of vehicle available

$$\sum_{j\in J} z_{jv}^{t} + \sum_{e\in E} z_{ev}^{t} \leq N_{v}^{t}\ \forall v, t = 1 \dots T \tag{30}$$

- Evacuation Constraint:
    - **Constraint 10**: Insures that every patient is evacuated, since the code is mathematical and the minimization objective might lead to achieving the minimum risk by not evacuating any patient at the end of T time intervals (if the threat risk is much lower than the transportation risk). Thus, this constraint will force the patients to be evacuated.

$$\sum_{j\in J}\sum_{v\in V}\sum_{t\in T} x_{epvt}^{j} = W_{pe} \quad \forall\, p \in P\ \forall\, e \in E \tag{31}$$

- Constraints 11-14 are the integrality and non-negativity constraints.
    - **Constraint 11:**

$$S_{epkt} \geq 0 \text{ and integer}, \forall\, p \in P, k \in K, e \in E, t = 1,2, \dots T \tag{32}$$

- **Constraint 12:**

$$x_{epvt}^{j} \geq 0 \text{ and integer}, \forall\, p \in P, v \in V, j \in J, e \in E, t = 1,2, \dots T \tag{33}$$

- **Constraint 13:**

$$y_{evt}^{j} \geq 0 \text{ and integer}, \forall\, v \in V, e \in E, j \in J, t = 1,2, \dots T \tag{34}$$

- **Constraint 14:**

$$y_{jvt}^{e} \geq 0 \text{ and integer}, \forall\, v \in V, e \in E, j \in J, t = 1,2, \dots T \tag{35}$$

CHAPTER 4

CASE STUDY: SINGLE HOSPITAL EVACUATION

This chapter discusses the evacuation of a single hospital due to a natural or a human-induced disaster. The mathematical optimization model involving single-hospital evacuation is deployed as explained in Chapter 3 and solved via ILOG CPLEX. This chapter presents an overview of the different parameters utilized in this case study, the methodology and analysis, problem instance, solution, and finally a discussion of the resulting performance measures per the model's objective function and the corresponding optimal values yielded by solving it.

4.1. Case Parameters

In this case, we consider the evacuation of a single hospital to a set of receiving hospitals, the process of which is illustrated in Figure 1. The evacuation process starts by relocating patients from their designated wards and settings in the hospital being evacuated to the staging area by specialized evacuation teams of medics and nurses. Subsequently, the patients are loaded into ambulances and other specialized vehicles, each of which is assigned to transport specific types of patients. Finally, the patients are transported to and unloaded at the receiving hospitals. Accordingly, the parameters of the single-hospital evacuation problem are as follows:

There are nine possible patient types; Neonatal Intensive Care Unit with ventilator (VNICU), Neonatal Intensive Care Unit (NICU), Pediatric Intensive Care Unit with ventilator (VPICU), Pediatric Intensive Care Unit (PICU), Intensive Care Unit with ventilator (VICU), Intensive Care Unit (ICU), Bed-Bound (BB), Ambulatory Oxygen-Dependent (AOD), and other Ambulatory (OA).

Per the aforementioned evacuation process, patients must be moved to the staging area before being transported to alternative care facilities with the assistance of specialized evacuation teams. There are two types of evacuation teams according to the type of patients they are trained to assist. The first type of evacuation teams is specifically trained to help patients on ventilators, and hence this team will assist in moving patients of the VNICU, VPICU and VICU categories. This evacuation team type is denoted by T_v. On the other hand, the second type of evacuation teams, denoted as T_0, can aid any patients that do not require a ventilator, thus this team can move NICU, PICU, ICU, BB, AOD, and AO patients. The time required for a specialized team to move a patient to the staging area is denoted by τ_v for patients on ventilators and τ_o for other patients. Figure 3 is an illustration of the correlation between the different patient and evacuation team types.

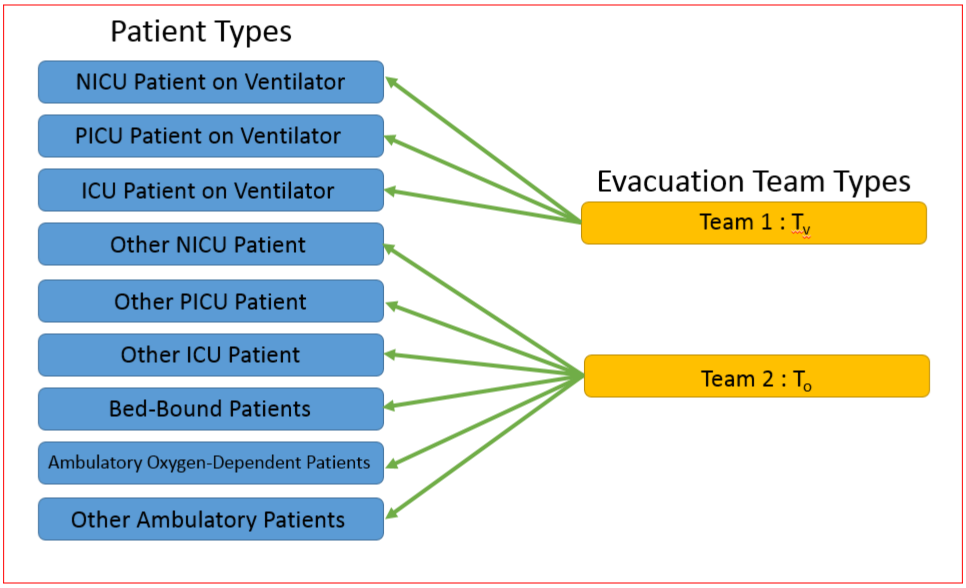


Figure 3: Patient and evacuation team types and correlation

Once at the staging area, the patients are loaded into their assigned vehicles and transported to the receiving hospitals. Four vehicle types are available to transport patients to the receiving hospitals: Critical Care Transport (CCT), Advanced Life Support (ALS) and Basic Life support (BLS) ambulances and buses. Each vehicle type can transport certain types of patients and has a physical capacity represented as the maximum number of patients who can be transported at a time. CCT vehicles can only transport one patient of the VNICU, VPICU, and VICU types at a time. ALS ambulances can only transport one NICU, PICU, or ICU patient at a time. BLS ambulances can transport BB and AOD patients with a capacity of two patients at a time. Finally, buses can transport up to thirty OA patients at a time, but cannot transport any other patient types. As aforementioned in Chapter 3, we assumed that each vehicle type has equal loading and unloading times which are independent of the patient types carried. The loading/unloading time is denoted as γ_v . Figure 4 demonstrates the association between the different vehicle and patient types.

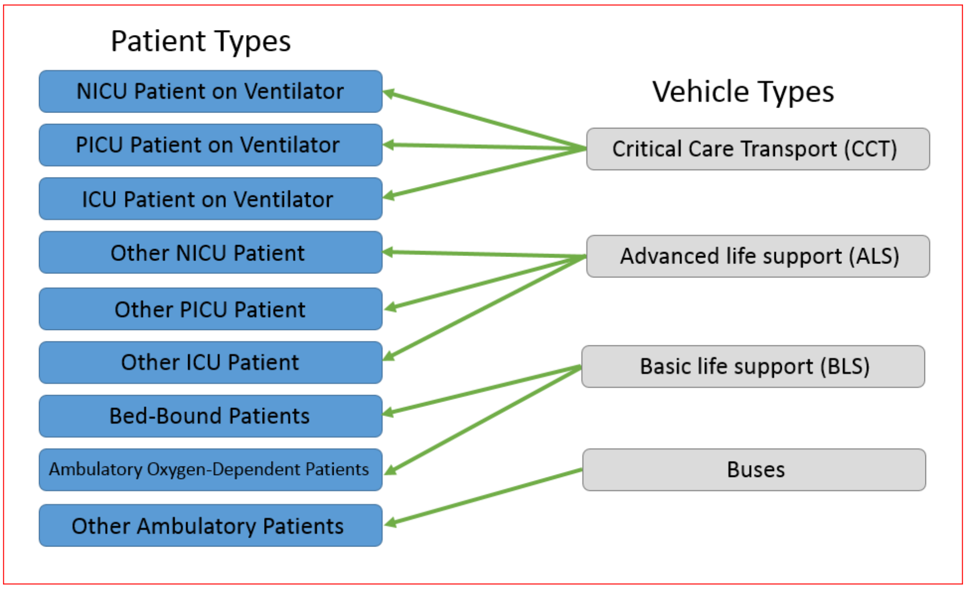


Figure 4: Patient and vehicle types and correlation

While patients are being loaded onto vehicles in the loading area, the vehicles occupy designated loading lanes. There are two types of loading lanes: ambulance lanes for the CCT, ALS, and BLS vehicles, and bus lanes, as illustrated in figure 5.

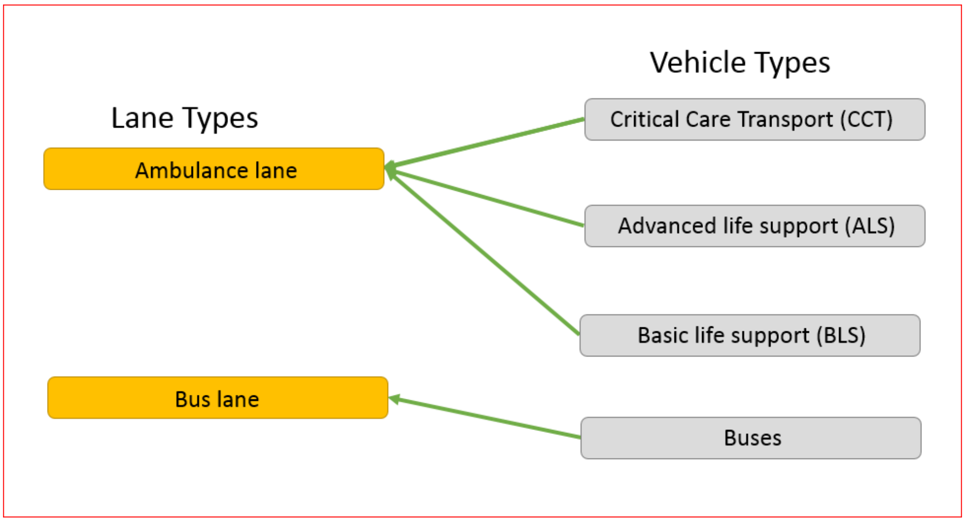


Figure 5: Lane and vehicle types and correlation

We assume that the traveling time between the evacuated hospital and each of the receiving hospitals is known and fixed throughout the problem. Each receiving hospital has a known number of available beds with four possible bed types corresponding to the patient types they can support: NICU beds for VNICU and NICU patients, PICU beds for VNICU and NICU patients, ICU beds for VICU and ICU patients, and regular beds for BB, AOD, and AO patients. The connection between the bed and patient types is illustrated in figure 6.

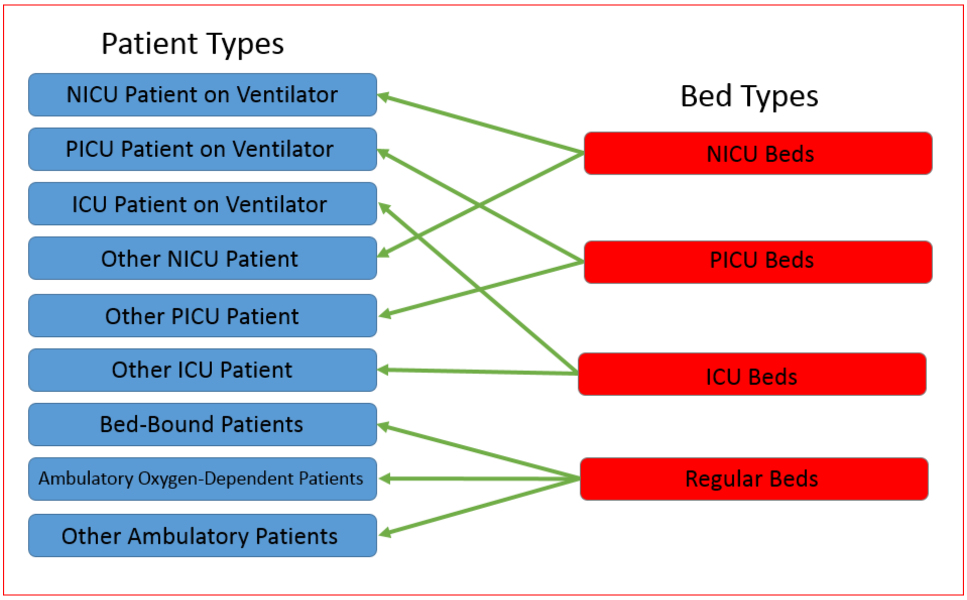


Figure 6: Patient and bed types and correlation

4.2. Methodology and Analysis

First the planning horizon of the single-hospital evacuation problem will be divided into equal time intervals. Therefore, parameters which are quantified as a function of time will be discretized to a number of time intervals to match the model. This is done by dividing the value of the parameter by the chosen length of the time interval and rounding up the resulting ratio to nearest integer in order to estimate the number of intervals. If the resulting ratio is not already an integer, the parameter would be overestimated, and so the optimal evacuation time generated by solving the model will always be an overestimation of the actual evacuation time required for the hospital. Consequently, choosing a smaller time interval would achieve better estimate of the evacuation time, but it would also render the problem less tractable due to the complex nature of the model and the problem itself. Similarly, choosing a larger time interval will adversely affect the quality of the solution, yet the same time facilitating solving the model. This analogy will be further illustrated while solving the single-hospital evacuation problem. The model will be solved twice based on 5-minute and 10-minute time intervals respectively. Given that the 10-minute interval length is a multiple of the 5-minute interval length, we anticipate achieving a better estimate of the optimal evacuation time using the 5-minute interval, but we also expect that the time required to solve the problem will be larger.

The objective is to minimize the overall risk on patients. Patients of each type are given threat risk and transportation risk coefficients. Minimizing the risk is highly correlated with minimizing the duration of the evacuation procedure. After realizing the minimum overall risk possible, we will be able to identify the limiting and excess resources (evacuation teams, vehicles, lanes, and beds) in the problem.

The lane utilization will be calculated using the following formula:

$$\frac{\sum_{t=1}^{T}\sum_{j\in J}\sum_{v\in V_i}\sum_{f=t-\gamma_v+1}^{t} y_{vf}^{j}}{T\times L_i}\times 100 \tag{36}$$

Where L_i is the number of lanes available of a type i, V_i is the set of vehicles allowed to use this lane, γ_v is the loading time of the patients onto the vehicle, and y_{vf}^{j} corresponds to the movement of the vehicles from the evacuated hospital.

Similarly the transport team utilization will be calculated using the following formulation:

$$\frac{\sum_{t=1}^{T}\sum_{k\in K_i}\sum_{p\in p_i}\sum_{f=t-\tau_p+1}^{t} S_{pkf}}{T\times K_i}\times 100 \tag{37}$$

Where K_i is the number of evacuating teams available of a type i, P_i is the set of patients that can be moved by this team type, τ_p is the moving time of patients from their wards to the staging area, and S_{pkf} corresponds to the movement of patients from their wards to the staging area.

The minimum number of idle vehicles will be calculated by:

$$N_{vt} - \max_{t} \sum_{f=max(t-\tau^{j},1)}^{t} y_{vf}^{j} \tag{38}$$

Where N_{vt} is the total number of available vehicles of type v at time interval t.

Accordingly, if we decrease the number of available vehicles by the above amount, the optimal solution will still be feasible, and having a non-zero value means that we have more assigned vehicles than needed for the evacuation process.

4.3. Problem Instance

In this case, 411 patients reside in the evacuated hospital, and they are distinguished by their types as shown in Table 1.

Table 1: Number of patients of each type in the evacuated hospital

Patient Type	Patient Type by Numbering	Number to Evacuate
VNICU	1	9
VPICU	2	10
VICU	3	16
NICU	4	12
PICU	5	15
ICU	6	36
BB	7	68
AOD	8	78
OA	9	167
Total		411

There are 60 potential receiving hospitals in this instance; the travel times to these hospitals from the evacuated hospital and their bed availability are summarized in Table 2. To move patients to the staging area, there are three evacuation teams to assist patients on ventilators and four evacuation teams to assist other patients. The times required to move patients are displayed in Table 3.

Six CCT, seven ALS, twenty seven BLS, and three buses are available throughout the evacuation process and time intervals. CCT and ALS ambulances have a loading and unloading time of 20 minutes, while it is 15 minutes for BLS ambulances, and 5 minutes for buses.

As mentioned earlier, this problem will be solved first using 5-minute time intervals and second using 10-minute intervals. Tables 2 and 3 present the times enumerated according to the 5-minute and 10-minute intervals respectively. Finally, this example has one ambulance lane and one bus lane for vehicle loading.

Table 2: Number of beds available at each receiving hospital, and their travel times from the evacuating hospital

Receiving hospitals (J)	Available NICU Beds	Available PICU Beds	Available ICU Beds	Regular Beds	10' Time Intervals	5' Time Intervals	Receiving hospitals (J)	Available NICU Beds	Available PICU Beds	Available ICU Beds	Regular Beds	10' Time Intervals	5' Time Intervals
1	0	3	0	0	1	1	31	1	1	0	4	2	3
2	1	2	0	8	1	1	32	0	0	2	3	2	3
3	0	0	4	2	1	1	33	18	5	8	51	2	3
4	0	0	1	2	1	1	34	0	0	1	4	2	3
5	0	0	1	4	1	1	35	4	0	2	8	2	3
6	0	0	0	2	1	1	36	0	0	2	8	2	3
7	4	3	0	0	1	1	37	0	0	1	1	2	3
8	0	0	5	4	1	1	38	0	0	1	2	2	4
9	1	2	2	1	1	1	39	0	0	0	7	2	4
10	2	0	0	1	1	2	40	1	0	0	3	2	4
11	0	0	2	2	1	2	41	0	0	1	6	2	4
12	6	1	2	2	1	2	42	6	0	1	3	2	4
13	0	0	0	3	1	2	43	2	0	0	2	2	4
14	0	0	1	4	1	2	44	4	0	0	4	2	4
15	2	5	2	8	1	2	45	0	0	2	3	2	4
16	10	0	0	15	1	2	46	2	0	1	6	2	4
17	13	3	0	20	1	2	47	1	3	1	3	3	5
18	7	0	8	40	1	2	48	3	0	1	2	3	5
19	3	0	3	18	2	3	49	0	0	0	2	3	5
20	0	0	0	5	2	3	50	5	0	0	9	3	5
21	0	0	1	7	2	3	51	1	1	1	2	3	5
22	3	0	5	0	2	3	52	0	0	1	21	3	5
23	0	2	2	0	2	3	53	1	0	2	22	3	5
24	2	1	0	3	2	3	54	8	1	8	34	3	5
25	0	0	1	2	2	3	55	1	0	2	0	3	5
26	0	0	1	7	2	3	56	0	1	1	1	3	5
27	2	0	1	3	2	3	57	2	0	0	3	3	5
28	0	0	5	9	2	3	58	19	0	1	22	3	5
29	0	0	0	8	2	3	59	0	0	1	3	3	5
30	1	1	1	2	2	3	60	1	0	0	3	3	5

Table 3: Moving time of patients by the evacuation teams to the staging area

Patient Type	Minutes	5 min Time Intervals	10 min Time Interval
VNICU	22	5	3
VPICU	22	5	3
VICU	22	5	3
NICU	10	2	1
PICU	10	2	1
ICU	10	2	1
BB	10	2	1
AOD	10	2	1
OA	10	2	1

As shown in Table 3, the time to move a ventilator patient to the staging area is 22 minutes. Based on the 10-minute intervals, 22 minutes round up to three 10-minute intervals which is equal to 30 minutes. Although the problem is easier to solve using the 10-minute interval, adding eight minutes to this task will definitely result in an overestimation of the evacuation time.

The instantaneous threat risk coefficients were assigned for each patient type as indicated in Table 4. Threat risk coefficients were assumed to stay the same throughout the evacuation process and time intervals. The cumulative threat risk was calculated using the corresponding instantaneous coefficients and the patients' moving times.

Table 4: Instantaneous threat risk for each patient type

Instantaneous Threat Risk								
1	2	3	4	5	6	7	8	9
0.02	0.02	0.02	0.008	0.008	0.008	0.004	0.004	0.002

The instantaneous transportation risk is presented in Table 5 and the cumulative risk is calculated using the instantaneous coefficients and the loading/unloading and travel times.

Table 5: Instantaneous transportation risk for each vehicle and patient type

Probability of Undesired Event in Each Time Interval (Transportation Risk)									
	1	2	3	4	5	6	7	8	9
CCT	0.001	0.0008	0.0007	0	0	0	0	0	0
ALS	0	0	0	0.001	0.00075	0.0007	0	0	0
BLS	0	0	0	0	0	0	0.001	0.001	0
BUS	0	0	0	0	0	0	0	0	0.0008

4.4. Solution

This problem was solved based on the 5-minute and 10-minute intervals. The base scenario considers 5-minute intervals, one ambulance lane and one bus lane. The solution of the base scenario converged to optimality in approximately 2 hours and 40 minutes. However, the bulk of the solving time was spent confirming optimality rather than finding it.

Given all scenarios presented for this problem, the base scenario which involves the 5-minute intervals and one ambulance lane is the most challenging because it has the highest number of time intervals as compared to solving the same problem using the 10-minure intervals and/or considering more than one ambulance lane. For instance, solving the problem based on one ambulance lane and 10-minute intervals, the solving time was about 13 minutes, which is drastically less than the problem based on the 5-minute intervals.

The objective function value, evacuation time, and solving time (i.e. running time) for the problem based on 5-minute and 10-minute intervals are displayed in Tables 6 and 7 respectively. For each time interval, four scenarios were considered, having one (original instance), two, or three ambulance lanes, and one bus lane. The forth scenario assumed that there exists an infinite number of ambulance and bus lanes. In other words, there is no physical loading capacity constraint under the fourth scenario.

Table 6: Evacuation time, objective function, and running time with 5 minutes time intervals

	Time Interval 5'				Solving (Running) Time
Number of Ambulance Lanes	Number of Time Intervals Used	Evacuation Time (Intervals)	Evacuation Time (Hours)	Objective Function	Minutes
1 Lane	650	650	54.16666667	38601.68	161
2 Lanes	400	317	26.41666667	14151.98	9
3 Lanes	250	245	20.41666667	9058.696	6
Infinity Lanes	200	200	16.66666667	5804.402	2

Table 7: Evacuation time, objective function, and running time with 10 minutes time intervals

	Time Interval 5'				Solving (Running) Time
Number of Ambulance Lanes	Number of Time Intervals Used	Evacuation Time (Intervals)	Evacuation Time (Hours)	Objective Function	Minutes
1 Lane	350	348	58	29417.08	13
2 Lanes	200	172	28.66666667	8506.022	3
3 Lanes	150	133	22.16666667	4869.521	2
Infinity Lanes	100	100	16.66666667	2838.194	0.5

The optimization model was run on ILOG CPLEX 12.6.1 with 2.00 Ghz Quad Core and 24 GB of RAM. Refer to appendix A for the algorithm used to solve case one.

The performance measures (utilization) of the different lanes and evacuation teams for the different scenarios are summarized in Tables 8 and 9.

Table 8: Performance measures with 5 minutes time intervals

	Utilization %			
Number of Ambulance Lanes	Ambulance Lane	Bus Lane	T_v -Teams	T_0 -Teams
1 Lane	100%	8%	10%	29%
2 Lanes	99%	11%	17%	59%
3 Lanes	98%	19%	22%	76%
Infinity Lanes	N/A	N/A	27%	94%

Table 9: Performance measures with 10 minutes time intervals

	Utilization %			
Number of Ambulance Lanes	Ambulance Lane	Bus Lane	T_v -Teams	T_0 -Teams
1 Lane	100%	13%	10%	27%
2 Lanes	100%	16%	19%	55%
3 Lanes	98%	30%	25%	71%
Infinity Lanes	N/A	N/A	33%	94%

Table 10 displays the minimum number of idle vehicles that will be waiting to enter their respective lanes and load patients from the evacuated hospital. The analysis was done on the various 5-minute-interval scenarios.

Table 10: Minimum number of idle vehicles by type for the 5 minutes intervals solutions

	Minimum number of Idle vehicles			
Number of Ambulance Lanes	CCT	ALS	BLS	Bus
1 Lane	3	4	23	1
2 Lanes	0	0	20	1
3 Lanes	0	0	15	1
Infinity	N/A	N/A	N/A	N/A

The number of the different bed types occupied in each receiving hospital is shown in Table 11. The results displayed belong to the original problem instance (one ambulance lane and 5-minute time intervals).

Table 11: Number of beds occupied at each receiving hospital

Receiving hospitals (J)	Occupied NICU Beds	Occupied PICU Beds	Occupied ICU Beds	Occupied Regular Beds	Occupied hospitals (J)	Occupied NICU Beds	Occupied PICU Beds	Occupied ICU Beds	Occupied Regular Beds
1	0	3	0	0	31	0	0	0	4
2	1	2	0	8	32	0	0	0	3
3	0	0	4	2	33	0	5	4	48
4	0	0	1	2	34	0	0	1	3
5	0	0	1	4	35	0	0	2	8
6	0	0	0	0	36	0	0	0	8
7	4	2	0	0	37	0	0	1	0
8	0	0	5	4	38	0	0	0	2
9	1	2	1	0	39	0	0	0	4
10	1	0	0	1	40	0	0	0	3
11	0	0	2	2	41	0	0	0	6
12	5	1	2	2	42	0	0	0	3
13	0	0	0	2	43	0	0	0	2
14	0	0	1	4	44	0	0	0	4
15	1	5	2	8	45	0	0	0	3
16	4	0	0	14	46	0	0	0	6
17	1	2	0	20	47	0	0	1	0
18	3	0	8	38	48	0	0	0	2
19	0	0	3	18	49	0	0	0	2
20	0	0	0	5	50	0	0	0	9
21	0	0	1	7	51	0	0	0	2
22	0	0	5	0	52	0	0	0	0
23	0	2	0	0	53	0	0	0	0
24	0	0	0	2	54	0	0	0	15
25	0	0	1	2	55	0	0	0	0
26	0	0	1	7	56	0	0	0	0
27	0	0	1	3	57	0	0	0	0
28	0	0	2	9	58	0	0	0	0
29	0	0	0	8	59	0	0	1	2
30	0	1	1	2	60	0	0	0	0

4.5. Discussion and Conclusion

In this section, the solutions for the different scenarios will be discussed and a conclusion will follow regarding the scarcity or the excess of the different resources. We will be referring to the tables in Sections 4.2. and 4.3. when discussing the different performance measures.

- **Risk Values**
    - **Threat Risk Rates**

The results obtained are based on equal instantaneous threat risk rates for all patients on ventilators (patients of type 1,2 and 3) and equal rates for patients of types 4,5 and 6. The rates decrease respectively for patients 7, 8 and 9 as shown in Table 4. When using different threat risk rates for each patient type, some patients will be given priority over others, and so the optimal solution would recommend an evacuating all patients from one type before starting with the other patient types, such that the evacuation pattern is sensitive to the risk priority. This would be unfair to the other patients who are assigned lower risk rates. Therefore, although there is a priority to some patients over others when using the chosen rates in the case, the evacuation pattern should be more mixed which is more realistic.

- **Transportation Risk Rates**

The instantaneous transportation risk rates are based on the type of vehicle and patient as shown in Table 5. Although a vehicle can transport a set of patient types, it will have a different risk impact on each different patient depending on the medical condition of the latter. A zero instantaneous risk value was assigned to the patients that cannot be transported on a given vehicle as shown in Table 5.

- **Time Intervals**

The number of time intervals affects the running time (time to achieve optimal solution) and the value of the objective function to some extent because occasionally, limiting the number of time intervals in which the total evacuation must take place, would results in the patients evacuated in an order different than the order they would have taken were they given more time. Hence, the solution would yield a higher optimal value as compared to the value resulting from utilizing more time intervals whereby some intervals will not be used (number of intervals will be in excess of the required evacuation time). For example, if we use 100 time intervals and the patients were indeed evacuated using all 100 time intervals, then there is a relatively high probability that the results are achieved in the most optimal way given the limitation imposed on the total number of time intervals. Thus the patients' evacuation order will differ and will give a lower optimal value if 150 intervals were given and100 or more were used up, so although more time intervals (evacuation time) are used, the order will change a bit to yield a lower optimal value.

Therefore, we have two options: using more time intervals and getting the absolute optimal value of the objective function or decreasing the time intervals as much as we possibly can while maintaining the feasibility of the problem. The evacuation constraint must be met and will aid us in determining the minimum number of time intervals that can be used for a given problem. Choosing to use high number of time intervals will require more solving time since increasing the total number of intervals by one unit increases the number of decision variables drastically and the running time will be higher. Despite the aforementioned, we will aim at achieving the best absolute solution. On the other hand, using a lower number of time intervals decreases the running time and saving time is key to the survival of disasters. For example, 650 time intervals required almost 3 hours while 200 required almost 2 minutes to solve the problem. In this problem, for the scenarios with one or infinity ambulance lanes and 5-minute intervals, the most feasibly minimum number of time intervals was chosen, which means that the objective function values aren't the absolute optimal values.

Finally, as apparent from the results obtained, increasing the number of ambulance lanes, allows more vehicles to evacuate patients concurrently, thus decreasing the total evacuation time. Hence, as we increased the number of lanes in each scenario, we decreased the total number of time intervals (T), decreasing by that the running time significantly as indicated by the results displayed in Tables 6 and 7.

- **Patients Evacuation Pattern**

Patients were being evacuated at a high frequency at the beginning of the process, after which the rate decreased and became relatively stable.

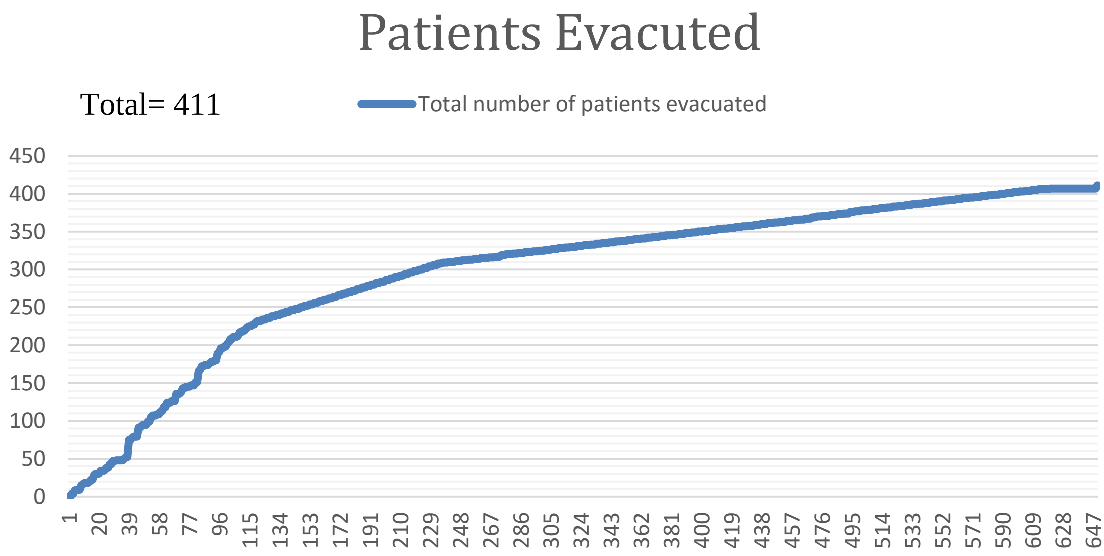
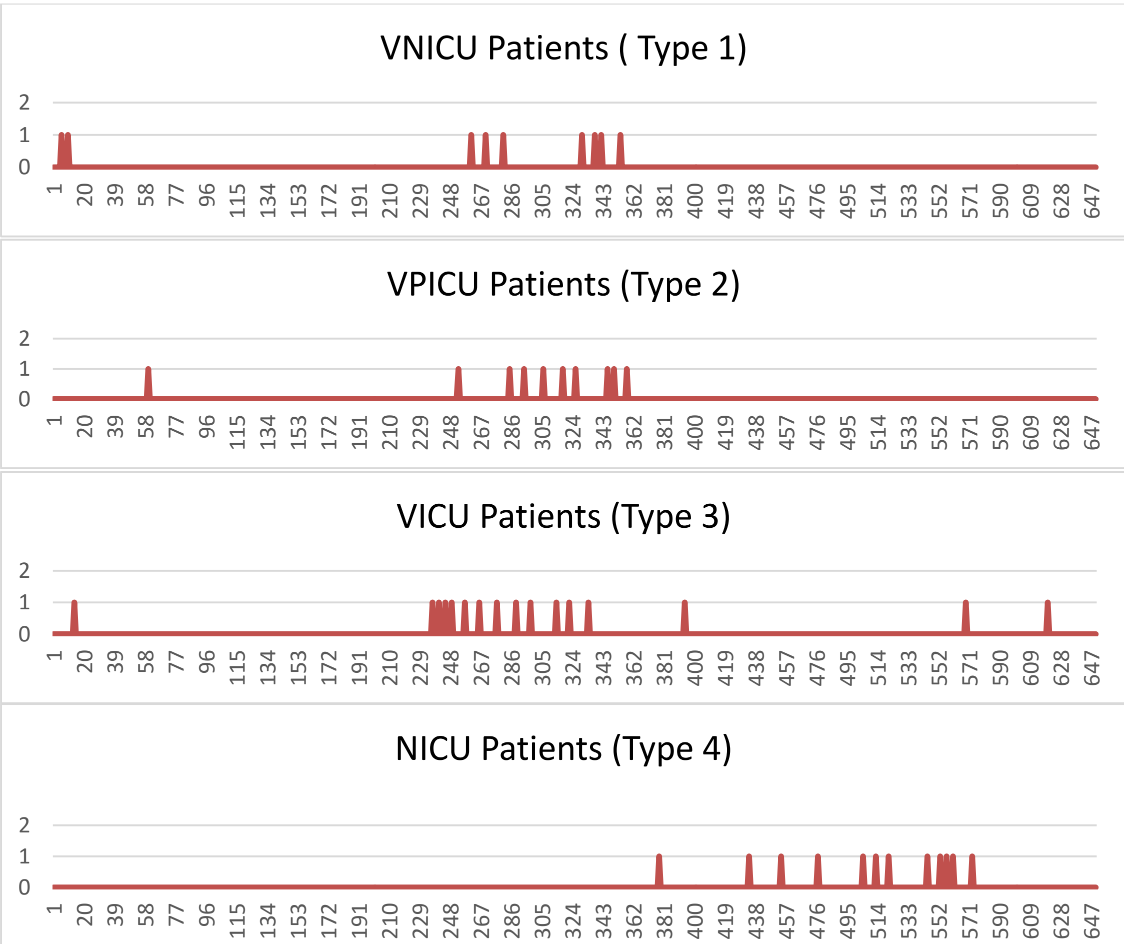


Figure 7: Total number of patients evacuated at time (t)

Patients 1 to 3 had similar evacuation patterns, so did patients 4 through 6, and 7 and 8 as well, thus only the corresponding graphs are shown in Figure 7 to infer the overall patient evacuation pattern. Although patients of type 1 through 3 have a higher threat risk, the number of type 7 and 8 patients was much higher and the optimal solution favored evacuating type 7 and 8 patients at first. Followed by patients 1,2 and 3; and then patients 4 through 6 which have a less overall risk than the first three patient types and are found in almost the same numbers. Patients of type 9 evacuated the hospital using the bus lane and will leave at the beginning of the evacuation process. Figure 8 presents the evacuation pattern for all patients belonging to each patient type.



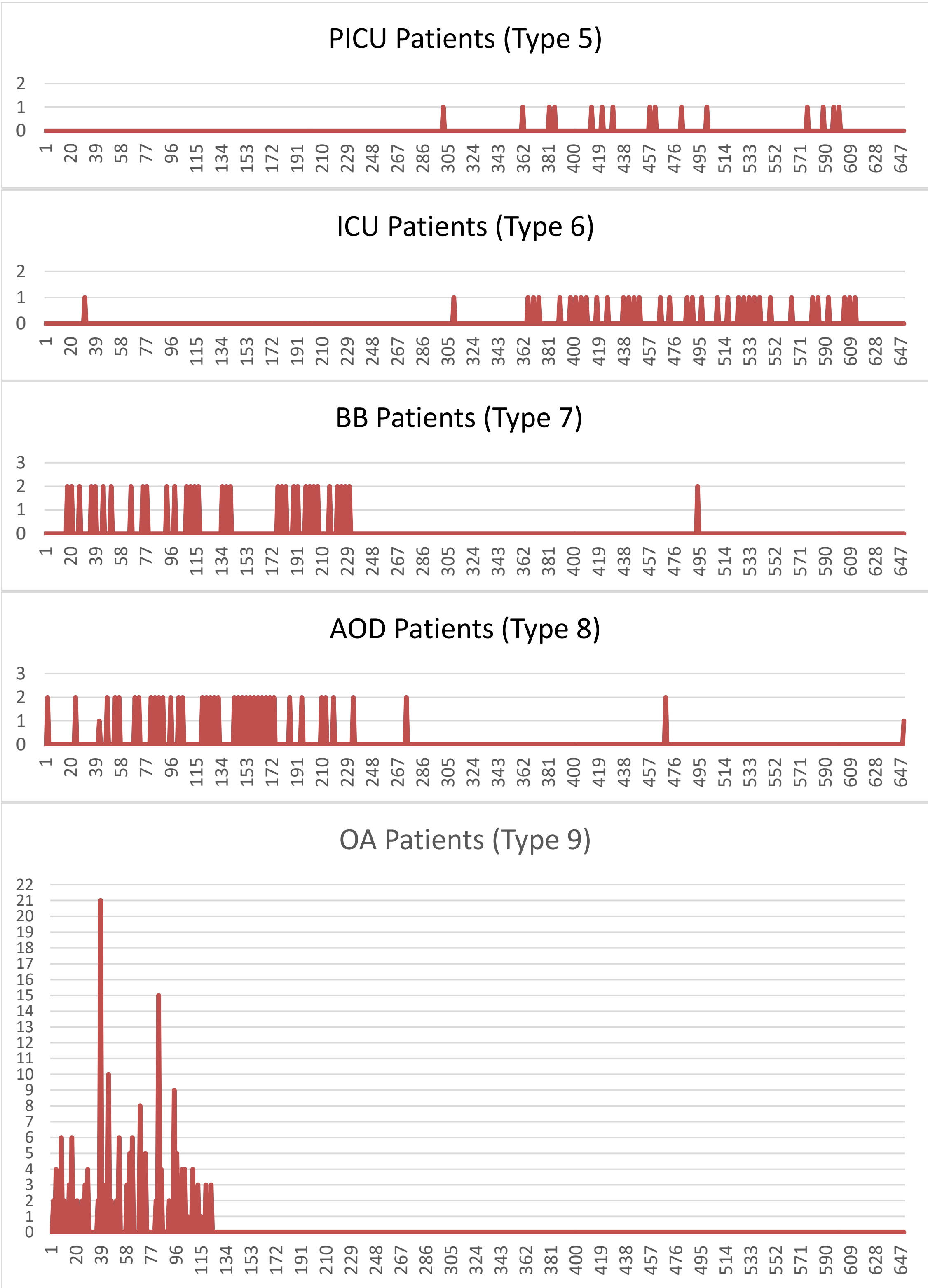


Figure 8: Patients being evacuated at each time (t), categorized by patient type

- **Patients to Receiving hospitals:**

The way the model works, patients were matched with a receiving hospital by two means, the bed availability in the hospital and the traveling time between the receiving and evacuating hospital. The results indicated that the beds were filled at first in receiving hospitals that were located relatively closer to the evacuating hospital, which eventually yielded in having the beds being fully occupied in the closest hospitals; while the ones farthest are filled but don't essentially reach the maximum bed capacity.

- **Ambulance Lane Utilization**
  - **5-minute Time Intervals**

In the original case where we have one ambulance lane, the corresponding utilization is 100% which implies that the lane was being used throughout all the evacuation process and that the vehicles were in excess waiting to enter the lane and load patients. This is presented by the minimum number of idle vehicles that was found. We can observe that there is at least 3 CCT, 4 ALS, and 23 BLS idle ambulances, this implies that we can reduce the number of available CCT by 3, ALS by 4 and BLS by 23 and not impact the current optimal solution, where the limiting factor (resource) in this setup is the number of available ambulance lanes.

In the second case, which considers having two ambulance lanes, the utilization is 99%, which implies that at some time intervals, vehicles were not available to load patients. The number of idle ALS and CCT ambulances was found to be zero during some time intervals, while BLS had at least 20 idle vehicles throughout the process.

Although there is an excess number of BLS ambulances, all the patients that could be loaded onto this vehicle type were already evacuated prior to the time intervals where the ALS and CCT weren't available to load patients, thus the lanes were empty during these time intervals. In the third case, which states having three ambulance lanes, the utilization is 98% with the same rationale as the second case.

Figure 9 illustrates the utilization of the lanes in each case, having a value of 1 indicates that the lanes are being used, while a value of zero indicates that the lane is empty. Table 12 is a summary of the results discussed; these results are also found in tables 8 and 10, in section 4.4.

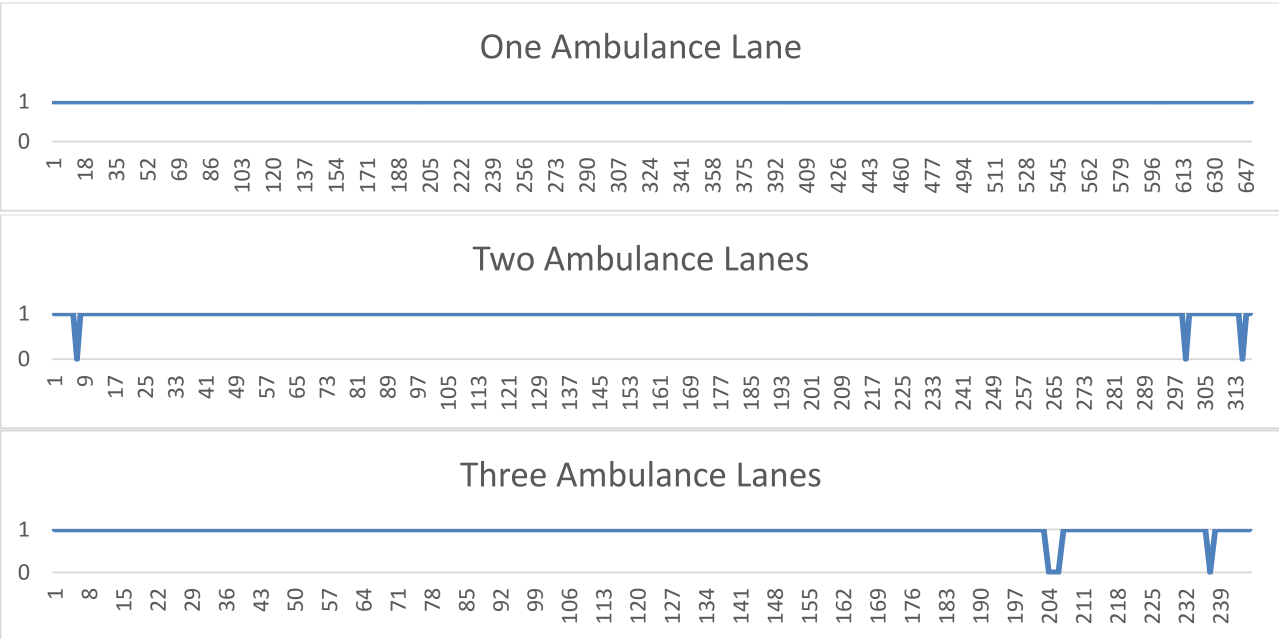


Figure 9: Ambulance lane utilization graphs for each scenario, with 5 minutes time intervals

Table 12: Minimum number of idle vehicle and lane utilization in each scenario, with 5 minutes time intervals

	Minimum number of Idle vehicles			
Number of Ambulance Lanes	CCT	ALS	BLS	Utilization %
1 Lane	3	4	23	100%
2 Lanes	0	0	20	99%
3 Lanes	0	0	15	98%
Infinity	N/A	N/A	N/A	N/A

- **10-minute Time Intervals**

The results obtained yielded similar utilization factors and conclusions. The ambulance lane utilizations for each scenario with 10-minute time intervals are shown in Table 10 in section 4.4.

- **Final Note**

Upon increasing the number of lanes from one to two lanes the evacuation time decreased to almost half the time, showing the extent to which the ambulance lane was a limiting resource. However, when moving from two to three to infinite lanes the evacuation time decreased, but not by much since the number of lanes were not the limiting resource, the vehicles were.

- **Bus Lane Utilization**

In all the scenarios proposed the utilization is not 100%, although there exists at least 1 idle bus during the evacuation process in each of these setups. This proves that the reason behind not having a 100 % utilization, is the number of patients and their availability at the staging area throughout the evacuation process. The patients being loaded onto buses were evacuated at the beginning of the evacuation process on a separate lane (bus lane) leaving no patients available to be loaded during the rest of the evacuation process and time intervals, hence leaving the bus lane idle during these time intervals. The utilization amplified as we increased the number of ambulance lanes because the overall number of time intervals were reduced, decreasing by that the time intervals were the lane was idle. Figure 10 demonstrates the utilization of the bus lanes in each of the scenarios with 5-minute time intervals. While Table 13 summarizes the results discussed, these results are also found in Tables 8, 9, and 10, in section 4.4. Finally, as a conclusion, the buses could be decreased by 1 without affecting the solution since there is at least as excess of 1 during the evacuation process.

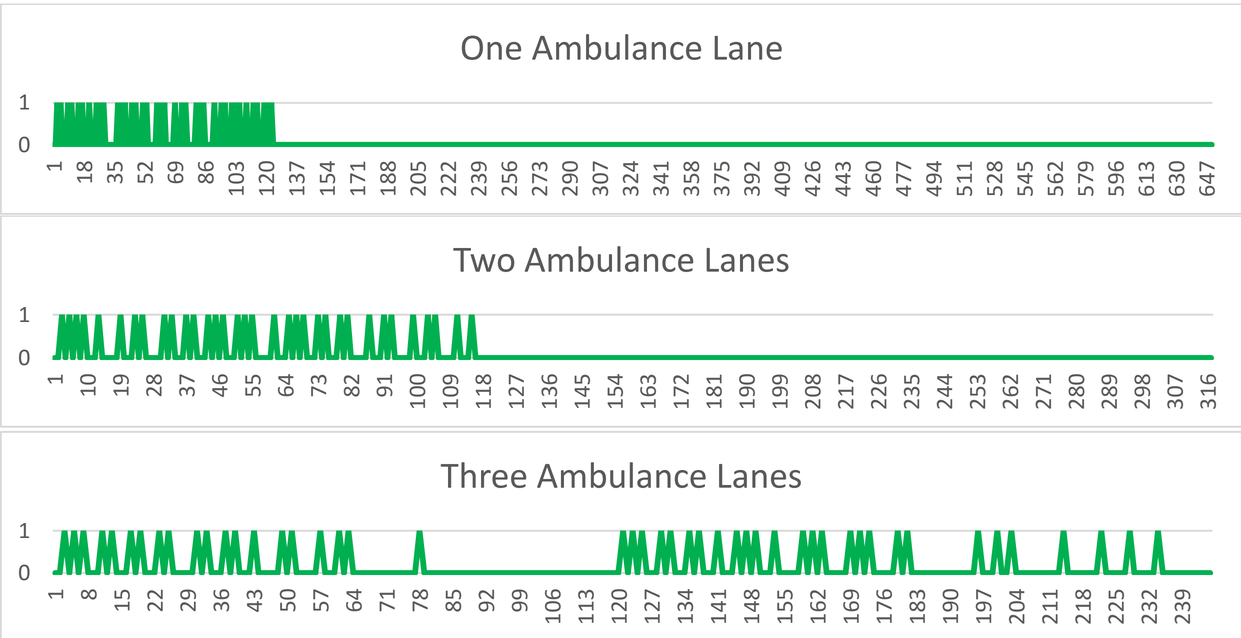


Figure 10: Bus lane utilization graphs for each scenario, with 5 minutes time intervals

Table 13: Minimum number of idle buses and bus lane utilization in each scenario, with 5 and 10 minutes time intervals

	Bus Lane Utilization %		Minimum number of idle buses
Number of Ambulance Lanes	5' time intervals	10' time intervals	
1 Lane	8%	13%	1
2 Lanes	11%	16%	1
3 Lanes	19%	30%	1
Infinity Lanes	N/A	N/A	N/A

- **Evacuation Team Utilization**

The teams are not being fully utilized since the patients are being moved to the staging area during the earliest time intervals, thus during the rest of the time intervals the teams are idle yielding a low utilization rate. As the number of time intervals is decreasing the utilization will increase, since the total number of time intervals where the teams are being utilized is almost the same but the overall number of time intervals is decreasing. Tables 8 and 9 summarize the utilization of the teams for the different scenarios and for the 5-minute and 10-minute time intervals respectively. The utilization factors, as well as Figures 11 and 12 which display graphically the utilization of team one and two respectively, indicates that the evacuation teams are an excess resource and we can decrease this resource without affecting the solution.

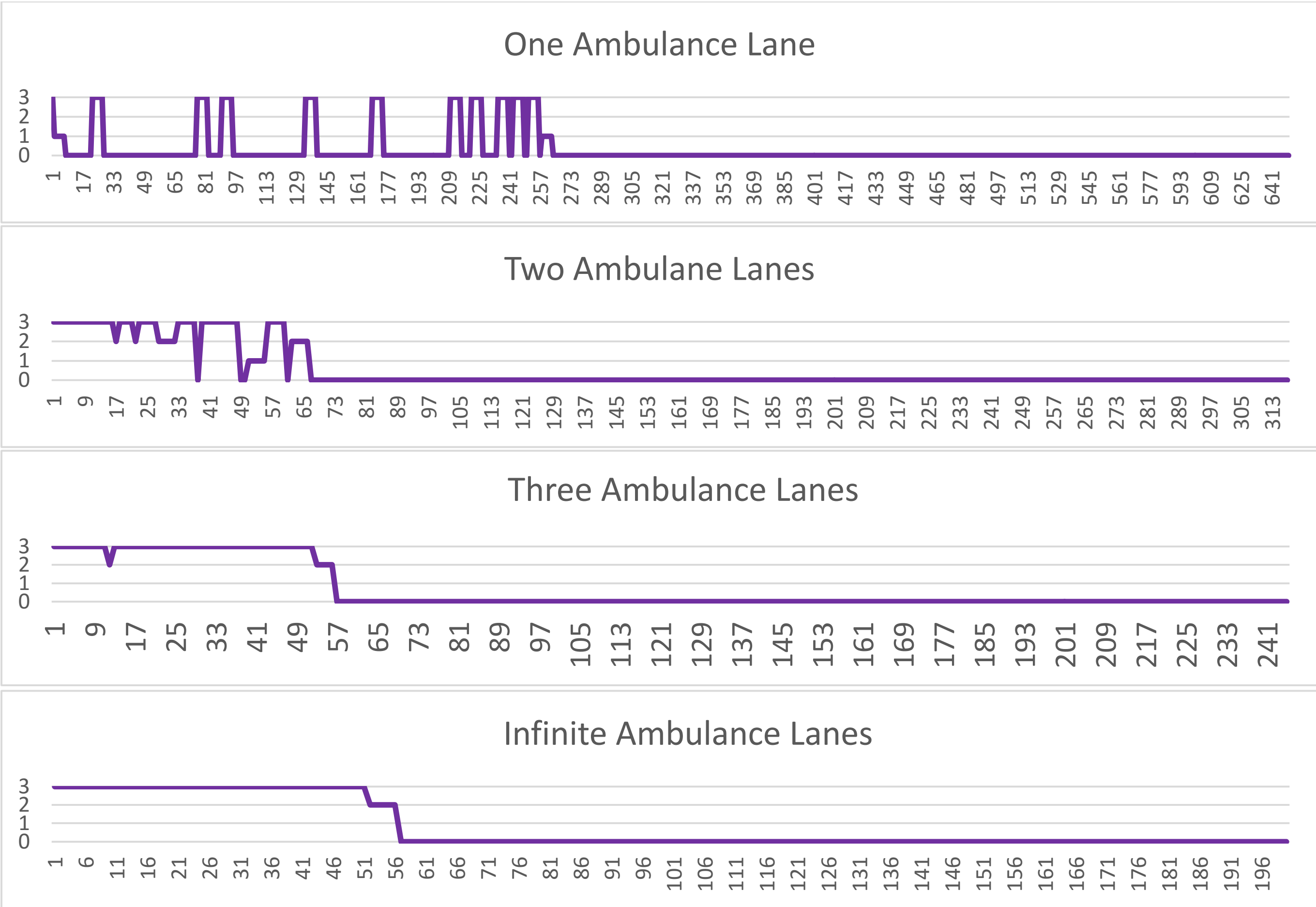


Figure 11: Team one (T_v) graphs for each scenario, with 5 minutes time intervals

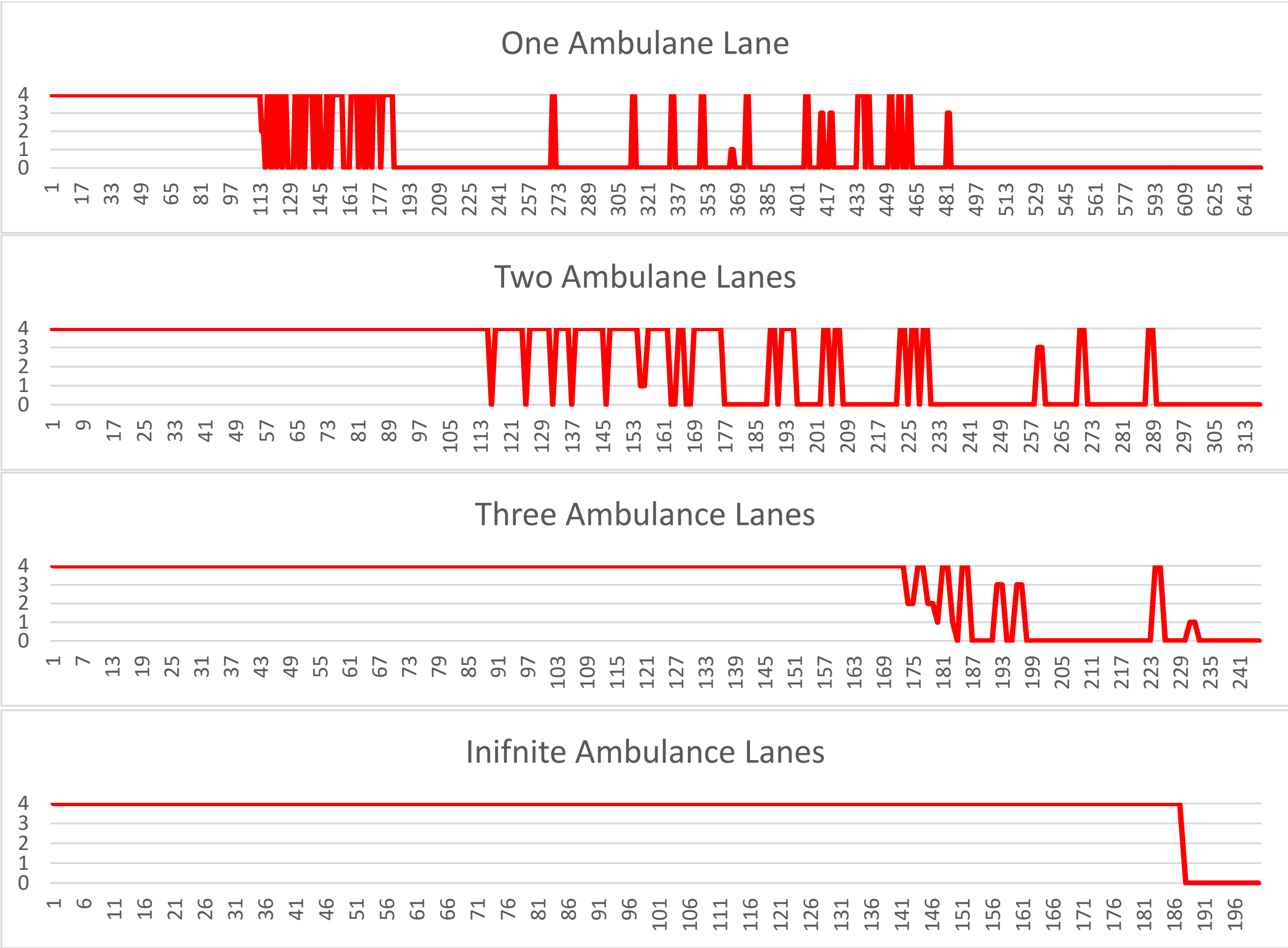


Figure 12: Team two (To) graphs for each scenario, with 5 minutes time intervals

- **Vehicle Utilization: Minimum Number of Idle Vehicles**

The minimum number of idle vehicles presented in Table 11 in section 4.4. allowed us to infer that the vehicles were the limiting resources in our problem when there were 2 or more ambulance lanes; where in the original instance the ambulance lane was the limiting resource.

- **Comparisons of some figures to when using 10-minute instead of 5-minute intervals**

The main issue is that the evacuation time, using a 10-minute time interval means rounding up to 10 minutes so we will be over estimating the evacuation time in comparison to when using the 5-minute time interval. This is shown in Tables 6 and 7, where when using 10- minute time intervals, the total evacuation time will be higher, in comparison to when using the 5-minute time intervals. Moreover, as we decrease the number of time intervals while moving from one scenario to the other we notice that the gap difference in evacuation time will decrease between the two cases until we reach the infinite lanes, where they will become the same. Since as the number of time intervals decrease the number of minutes rounded up would decrease, thus the time difference would diminish. Utilization factors are noticed to have the same pattern and almost the same utilization

Finally, there were minor changes when matching between patients and the receiving hospitals, since hospitals that were 1 and 2 time intervals away from the evacuating hospital when using the 5 minutes time intervals, both became 1 time interval away when using the 10 minutes time interval, giving them equal transportation risks. Henceforth, since vehicles couldn't make multiple stops, and since a single vehicle could carry sometimes two or more patients that will be situated in different bed types in the receiving hospitals, matching between the patients in the vehicles and the bed availability for these patients in the hospitals became the main differentiating factor amongst the different receiving hospitals. Keeping in mind that traveling time still played a major factor as well.

CHAPTER 5

CASE STUDY: MULTI-HOSPITAL EVACUATION

The case presented and discussed hereafter involves multi-hospital evacuation due to a natural or human-induced disaster. The mathematical model of multi-hospital evacuation will be utilized and run on ILOG CPLEX to achieve the optimal solution for the corresponding objective function. This chapter presents an overview of the different parameters utilized in this case study, the methodology and analysis, problem instance, solution, and finally a discussion of the resulting performance measures per the model's objective function and the corresponding optimal values yielded by solving it.

5.1. Case Parameters

There are nine possible patient types, two evacuation team types, four vehicle types, two lane types, and four bed types having the same classifications and responsibilities presented in Chapter 4. Accordingly, each vehicle type can cater for certain patient types, while having a maximum allowable number of patients in the vehicle at a time. The vehicles' capacities assignment is similar to that deployed in the single-hospital evacuation problem presented in Chapter 4. Similar parameters were used such that the results of the multi-hospital evacuation can be compared and assessed in the light of those of the single-hospital evacuation. Figure 3, 4, 5, and 6 present and illustration of the various relationships between the different parameters.

Nonetheless, this case differs from the first in the numbers of evacuating and receiving hospitals, such that there are three evacuating hospitals and sixteen receiving hospitals. The number of receiving hospitals was decreased from 60 to 16 because the number of decision variables in the multi-hospital evacuation model is much higher than the variables in the single-hospital evacuation. Therefore, considering one additional hospital would increase the number of decision variables drastically and inherently increase the solving time.

5.2. Methodology and Analysis

This problem will be solved using the optimization model for multi-hospital evacuation described earlier in Chapter 3. In this case, 10-minute intervals will be used, and therefore, the results obtained and the optimal solution generated will always be an overestimation of the actual evacuation time of the hospitals. Although choosing a smaller time interval would produce a better solution, it makes the problem less tractable due to the complexity of the model. 5-minute intervals weren't used since this would have significantly increased the number of decision variables. However, 5-minute intervals were tested and the running time was very high, and given this, in some extreme cases we were encountering an error which stated that the computer's memory was not sufficient to store all the variables. Hence, the solution and analysis is based on the 10-minute interval.

The objective is to minimize the overall threat and transportation risk on patients, which is indicated by the corresponding instantaneous risk coefficients.

Minimizing the risk is highly correlated with minimizing the evacuation duration. After determining the optimal solution, we will identify the limiting and excess resources (evacuation teams, vehicles, lanes, and beds) in the problem.

The lane utilization in each evacuating hospital will be calculated using the following formula:

$$\frac{\sum_{t=1}^{T}\sum_{j\in J}\sum_{v\in V_i}\sum_{f=t-\gamma_v+1}^{t} y_{evf}^{j}}{T\times L_{i_e}}\times 100 \tag{39}$$

Where $L_{i_e}$is the number of lanes available of a type i in evacuating hospital e, V_i is the set of vehicles allowed to use this lane, γ_v is the loading time of the patients onto the vehicle, and y_{evf}^{j} corresponds to the movement of the vehicles from evacuating hospital e.

Similarly, the transport team utilization in each evacuating hospital will be calculated using the following formula:

$$\frac{\sum_{t=1}^{T}\sum_{k\in K_{e_i}}\sum_{p\in p_{e_{ki}}}\sum_{f=t-\tau_{pe}+1}^{t} S_{epkf}}{T\times K_{e_i}}\times 100 \tag{38}$$

Where $K_{e_i}$is the number of evacuating teams available of a type i at evacuating hospital e, $p_{e_{ki}}$ is the set of patients in hospital e that can be moved by this team type, τ_{pe} is the moving time of the patients from their ward to the staging area in hospital e, and S_{epkf} corresponds to the movement of the patients from their ward to the staging area at evacuating hospital e.

The minimum number of idle vehicles will be calculated by:

$$N_{vt} - \max_{t} \sum_{j \in J} z_{jv}^{t} + \sum_{e \in E} z_{ev}^{t} \qquad (39)$$

Where N_{vt} is the total number of available vehicles of type v at time interval t. z_{jv}^{t} is the number of vehicles of type v found or are on their way to the receiving hospital j at time t. z_{ev}^{t} is the number of vehicles of type v found in or are on their way to evacuating hospital e at time t

Accordingly, if we decrease the number of available vehicles by the above amount, the optimal solution will still be feasible, and having a non-zero value means that we have more assigned vehicles than needed for the evacuation process.

5.3. Problem Instance

The case presented in this chapter involves 913 patients that need to be evacuated from three hospitals simultaneously. The distribution and classification of patients by type and number among the three hospitals to be evacuated are presented in Table 14.

Table 14: Number of patients of each type in each evacuating hospital

Patient Type	Patient Type by Numbering	Patients to be Evacuated Hospital 1	Patients to be Evacuated Hospital 2	Patients to be Evacuated Hospital 3	Total Number of Patients
VNICU	1	5	4	6	15
VPICU	2	7	10	6	23
VICU	3	8	7	10	25
NICU	4	5	8	6	19
PICU	5	6	5	7	18
ICU	6	9	7	8	24
BB	7	56	62	49	167
AOD	8	60	62	56	178
OA	9	155	149	140	444
Total		311	314	288	913

There are 16 potential receiving hospitals in this instance; the travel times from these hospitals to the evacuating hospital and the bed availability is provided in Table 15.

Table 15: Number of beds available at each receiving hospital, and their travel times from the evacuating hospitals

Receiving hospitals (J)	Available NICU Beds	Available PICU Beds	Available ICU Beds	Regular Beds	10' Time Intervals From Hospital 1	10' Time Intervals From Hospital 2	10' Time Intervals From Hospital 3
1	3	5	8	94	1	1	1
2	4	6	19	39	1	1	1
3	1	4	0	26	1	1	1
4	2	0	6	63	1	1	1
5	1	5	7	25	2	2	2
6	0	0	6	51	2	2	2
7	0	3	7	78	2	2	2
8	5	0	5	27	2	2	2
9	4	6	12	41	2	2	2
10	0	2	5	28	2	2	2
11	6	0	0	30	2	2	2
12	2	4	7	74	2	2	2
13	6	0	0	36	2	2	2
14	1	5	2	53	2	2	2
15	4	3	3	69	2	2	2
16	0	6	1	73	2	2	2

The numbers and types of available evacuation teams that are responsible to move the patients to the staging area in each evacuated hospital are presented in Table 16. The required time to move the patients by these teams in each hospital is shown in Table 17.

Table 16: Available evacuation teams in each hospital

Hospital 1	Tv	2
	To	3
Hospital 2	Tv	3
	To	3
Hospital 3	Tv	2
	To	2

Table 17: Patients moving time from each evacuating hospital

	Hospital 1		Hospital 2		Hospital 3	
Patient Type	Minutes	10 min Time Intervals	Minutes	10 min Time Intervals	Minutes	10 min Time Intervals
VNICU	15	2	18	2	18	2
VPICU	15	2	18	2	18	2
VICU	15	2	18	2	18	2
NICU	8	1	10	1	9	1
PICU	8	1	10	1	9	1
ICU	8	1	10	1	9	1
BB	8	1	10	1	9	1
AOD	8	1	10	1	9	1
OA	8	1	10	1	9	1

Nine CCT, eleven ALS, twenty seven BLS, and ten buses are available throughout the evacuation process and time intervals. CCT and ALS ambulances have a loading and unloading time of 20 minutes, while it is 15 minutes for BLS ambulances, and 5 minutes for buses.

As shown in Table 17, although the time to move a ventilator patient to the staging area in each evacuating hospital differs slightly, rounding up the latter per the 10-minute time interval will result in close estimates of the corresponding moving times.

The instantaneous threat risk coefficients were assigned for each patient type in each evacuated hospital as shown in Table 18. These coefficients were assumed constant throughout the evacuation process and time intervals. The cumulative threat risk was calculated using the instantaneous coefficients and the patients moving times.

Table 18: Instantaneous threat risk for each patient type

	Instantaneous Threat Risk								
	1	2	3	4	5	6	7	8	9
H1	0.02	0.02	0.02	0.008	0.008	0.008	0.004	0.004	0.002
H2	0.019	0.019	0.019	0.009	0.009	0.009	0.005	0.005	0.0015
H3	0.022	0.022	0.022	0.008	0.008	0.008	0.005	0.005	0.002

The instantaneous transportation risk is presented in Table 19 and the cumulative risk is calculated using the instantaneous coefficients along with the loading/unloading and travel times.

Table 19: Instantaneous transportation risk for each vehicle and patient type

Probability of Undesired Event in Each Time Interval (Transportation Risk)									
	1	2	3	4	5	6	7	8	9
CCT	0.001	0.0008	0.0007	0	0	0	0	0	0
ALS	0	0	0	0.001	0.00075	0.0007	0	0	0
BLS	0	0	0	0	0	0	0.001	0.001	0
BUS	0	0	0	0	0	0	0	0	0.0008

5.4. Solution

As mentioned earlier, this case study was solved using 10-minute time intervals. The main scenario was considered to comprise of one ambulance lane and one bus lane in each evacuated hospital. The solution was found to converge to optimality in approximately 3 hours and 7 minutes. However, the majority of the solving time elapsed to confirm optimality and not to find it.

Of all scenarios presented for this case study, solving the problem with one ambulance lane is the most challenging, because it has the highest number of time intervals in comparison to when solving the problem with more than one ambulance lane. For instance, when solving the problem with two ambulance lanes, the solving time was about 23 minutes, which is drastically less than the problem with one ambulance lane.

The objective function value, the evacuation time, and the solving time (i.e. running time) for the problem based on the 10-minute intervals are presented in Table 20. For each time interval, four scenarios were considered, having one (original instance), two, three ambulance lanes; along with one bus lane. The forth scenario assumed that there exists infinite number of ambulance and bus lanes, and in other words, there is no physical loading capacity constraint .

Table 20: Evacuation time, objective function, and running time with 10 minutes time intervals

	Time Interval 5'				Solving (Running) Time
Number of Ambulance Lanes	Number of Time Intervals Used	Evacuation Time (Intervals)	Evacuation Time (Hours)	Objective Function	Minutes
1 Lane	250	250	41.66666667	18724.2	187
2 Lanes	170	162	27	6713.09	23
3 Lanes	160	149	24.83333333	2772.351	6
Infinity Lanes	150	141	23.5	936.64	1

The optimization model was run on ILOG CPLEX 12.6.1 with 2.00 Ghz Quad Core and 24 GB of RAM. Refer to appendix B for the algorithm used to solve case two.

The performance measures (utilization) of the different lanes and evacuation teams for the different scenarios in each evacuating hospital are summarized in Table 21. The average utilization was calculated by adding the utilization of each hospital and dividing it by the number of hospitals being evacuated. Only ambulance lanes utilization will be presented in details in this table, since the ambulance lanes are the most important resource amongst the resources mentioned in this table. The average utilization for the other resources is presented in this table.

Table 21: Performance measures with 10 minutes time intervals

	Utilization						
Number of Ambulance Lanes	Ambulance Lane H1	Ambulance Lane H2	Ambulance Lane H3	Average	Average Bus Lane	Tv - Teams	T0 - Teams
1 Lane	98%	99%	96%	98%	15%	11%	42%
2 Lanes	93%	94%	90%	93%	16%	15%	56%
3 Lanes	82%	85%	81%	82%	17%	17%	57%
Infinity Lanes	N/A	N/A	N/A	N/A	N/A	17%	57%

Table 22 displays the minimum number of idle vehicles that will be waiting to enter the lane and load patients at the loading area in the evacuating hospital. The analysis was done on the various 10-minute-interval scenarios.

Table 22: Minimum number of idle vehicles by type for the 10 minutes intervals solutions

	Minimum number of Idle vehicles			
Number of Ambulance Lanes	CCT	ALS	BLS	Bus
1 Lane	0	0	19	1
2 Lanes	0	0	16	1
3 Lanes	0	0	11	1
Infinity	N/A	N/A	N/A	N/A

The numbers of the different bed types occupied in each receiving hospital are presented in Table 23. The results presented belong to the original problem instance (one ambulance lane and 10-minute time intervals).

Table 23: Number of beds occupied at each receiving hospital

Receiving hospitals (J)	Occupied NICU Beds	Occupied PICU Beds	Occupied ICU Beds	Occupied Regular Beds
1	3	5	8	94
2	4	6	18	39
3	1	4	0	26
4	2	0	6	63
5	1	5	7	25
6	0	0	6	51
7	0	3	2	78
8	5	0	0	27
9	4	6	2	41
10	0	1	0	22
11	5	0	0	30
12	2	2	0	74
13	4	0	0	35
14	1	3	0	45
15	2	3	0	69
16	0	3	0	67

5.5. Discussion and Conclusion

In this section, the solutions for the different scenarios will be discussed and a conclusion will be formed regarding the scarcity or the excess of the different resources. We will be referring to the tables in section 5.3. and 5.4. when discussing the different performance measures.

The numbers were chosen, almost in a similar manner to the previous case discussed, this was done in order to be able to compare between the two results and solutions that we got.

- **Risk Values**
  - **Threat Risk Rates**

As with the first case, the solutions were based on equal instantaneous threat risk rates for all patients on ventilators (patients of types 1,2 and 3) and equal rates for patients of type 4,5 and 6. The rates decrease respectively for patients 7, 8 and 9 within the same hospital as shown in Table 18. The threat risk coefficients between the three hospitals were differed in order to assess whether this would create prioritization amongst the different hospitals or if it would produce a different evacuation pattern in each hospital.

When using different threat risk rates for each patient type, some patients will be given priority over others, the solution would have yielded an evacuation pattern which evacuated all patients from one type before starting with the others which is unfair to the other patients that are assigned lower risk rates. Therefore, although there is priority to some patients over others when using the chosen rates in the case, the evacuation pattern is more mixed which is more realistic.

- **Transportation Risk Rates**

The instantaneous transportation risk rates were taken based on the type of vehicle and patient as shown in Table 19. Although a vehicle can transport a set of patient types however it will have a different risk impact on each different patient depending on the medical condition of each type. A zero instantaneous risk value was assigned to the patients that cannot be transported on a given vehicle as shown in Table 19. The evacuated hospitals are assumed to be close to one another (within the area that was hit by the disaster). Thus the traveling times between them and the receiving hospitals when rounded to 10 minutes will be the same, which will give a similar transportation risk amongst the same patient types in the three evacuating hospitals.

- **Time Intervals**

The number of time intervals affects the running time and sometimes the value of the objective function, since occasionally by limiting the number of time intervals in which the total evacuation must take place, the patients might leave in an order different than the order they would have followed had they been given more time. Hence, the solution would yield a higher optimal value relative to the second optimal value when we are giving more time intervals in which not all intervals are used. In this problem, for the original scenario with one ambulance lane, the total number of time intervals (T) was assigned to be 250 time intervals, in which the patients were evacuated with an evacuation time of 250 time intervals. This means that the results are given in the most optimal way given the limitation imposed regarding the number of time intervals, thus the patients' evacuation order will differ and will give a lower optimal value had we given 280 intervals and 250 or more were used. Although more time intervals (evacuation time) were used, the order will change a bit to yield a lower optimal value.

Thus we have two options, using more time intervals and getting the absolute optimal value of the objective function; or decreasing the time intervals as much as we possibly can while maintaining the feasibility of the problem.

The evacuation constraint must be met and will aid us in determining the minimum number of time intervals that can be used for a given problem. Choosing to use a high number of time intervals will yield more solving time since as we increase one time interval the number of decision variables will increase drastically so the running time will be higher. However we will get the best absolute solution. On the other hand, using low number of time intervals will give a faster running time and saving time is a key to the success of any evacuation process. Bearing in mind the vast number of decision variables that would be added had we increased the time intervals from 250 to 280 intervals, the running time would have increased to approximately 4 hours, adding to the process one hour.

Finally, as we see from the results obtained increasing the number of ambulance lanes, allows more vehicles to evacuate patients concurrently, decreasing the total evacuation time in the process. Hence as we increased the number of lanes in each scenario we decreased the total number of time intervals (T) decreasing by that the running time significantly as seen in the results obtained in Table 20.

- **Patients Evacuation Pattern**

After getting the solution and raw data that describes the patients' evacuation pattern, it was observed that the three hospitals had similar evacuation patterns. Moreover, the overall evacuation as well as the patients' evacuation order were similar in all three evacuating hospitals, and were similar to the results and patient evacuation pattern observed and discussed in the single-hospital evacuation problem.

Patients were being evacuated at a high frequency at the beginning of the process, after which the rate decreased and became relatively stable as illustrated in Figures 13 and 14.

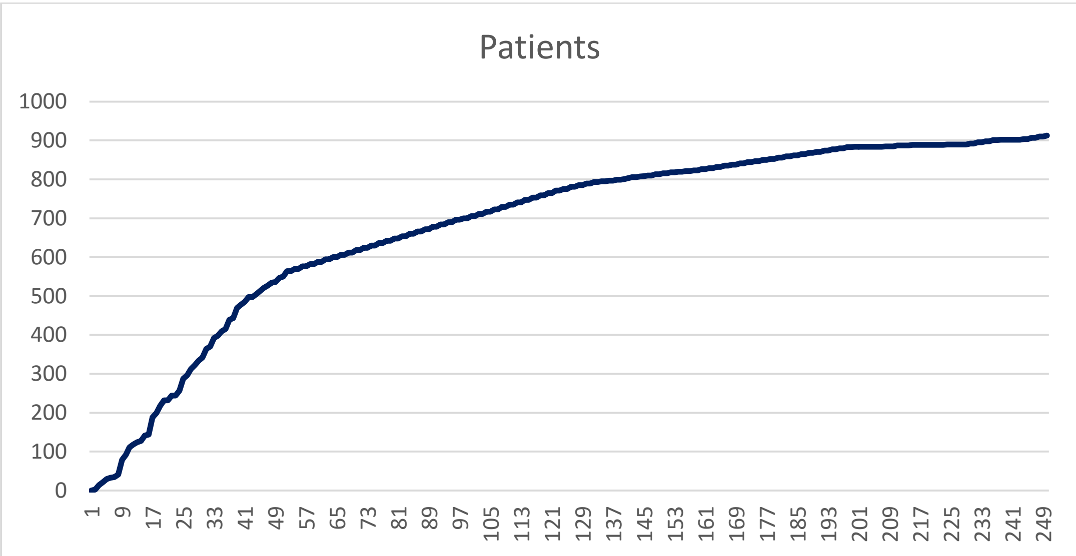


Figure 13: Total number of patients evacuated at time (t)

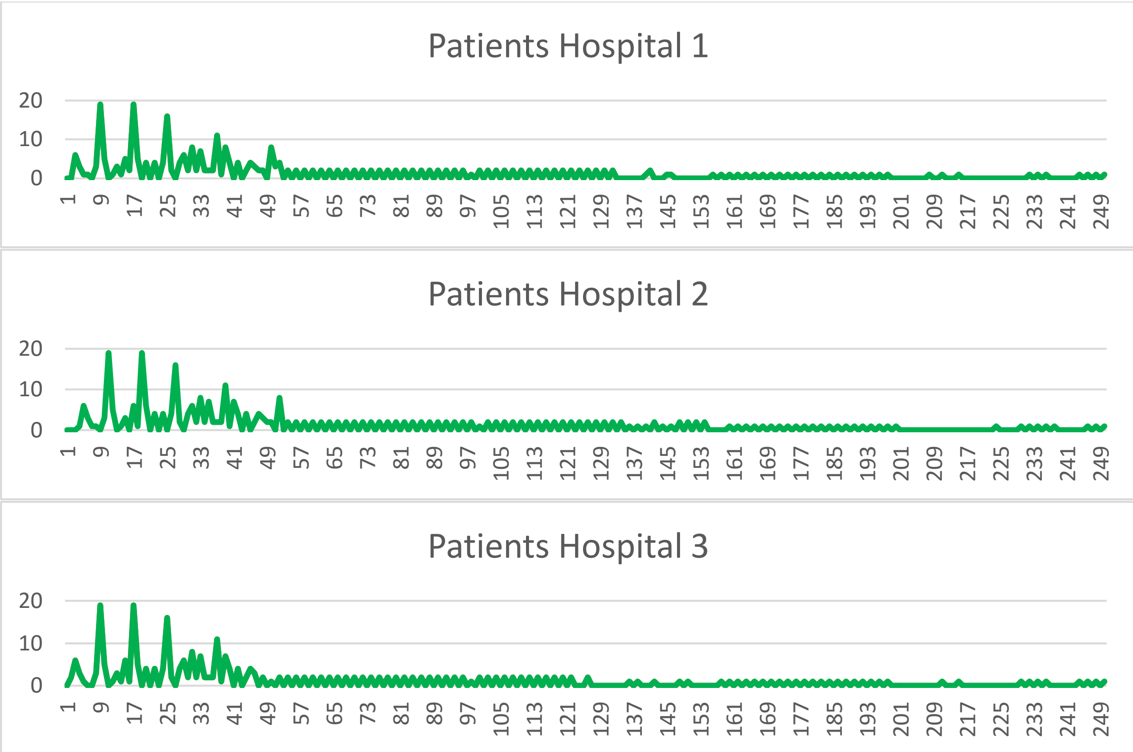
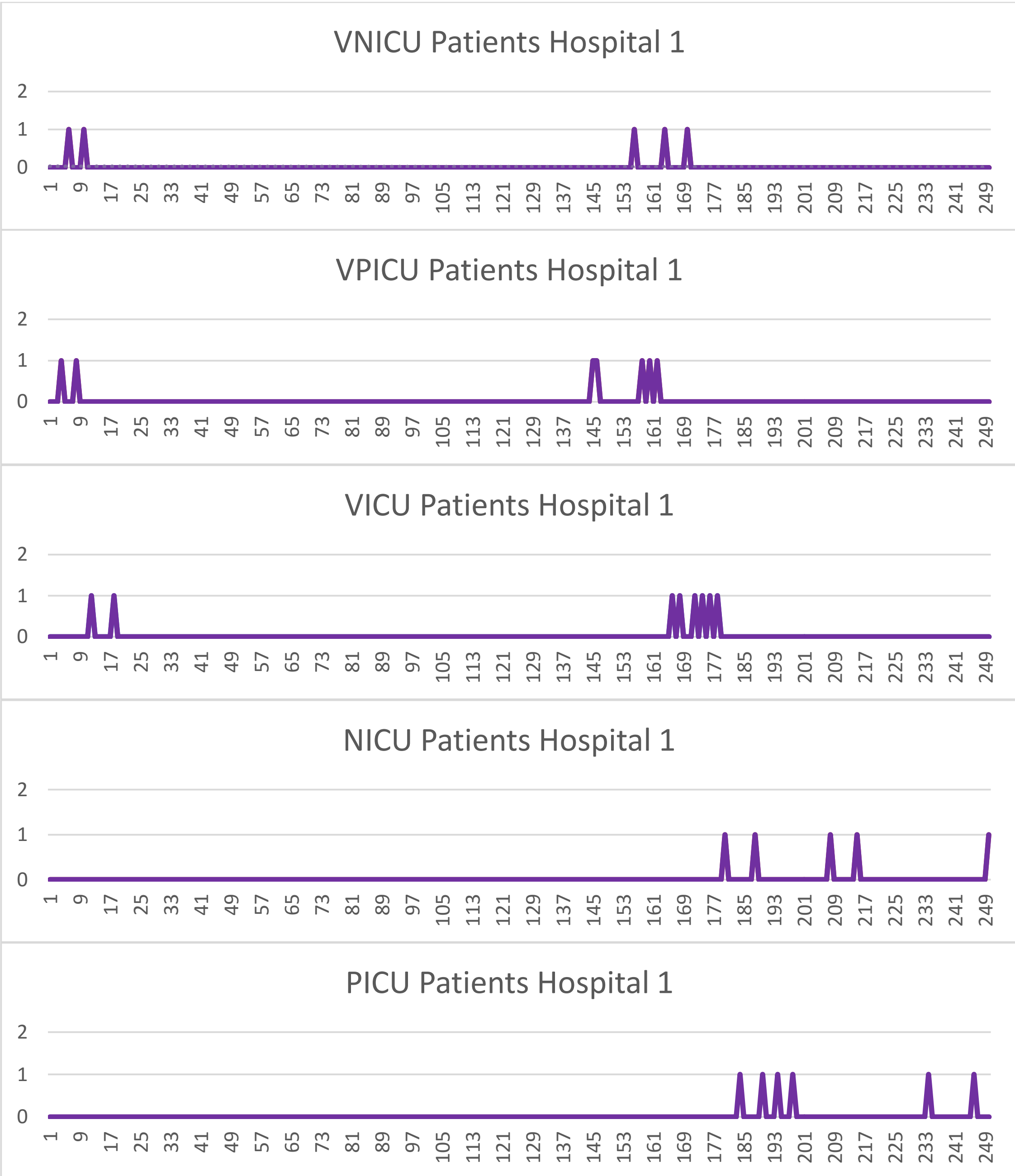


Figure 14: Number of patients evacuated at time (t)

In all three hospitals, patients that belonged to type 1, and 3 had a similar evacuation pattern; so did patient types 4 to 6. Patients 7 and 8 had as well a similar evacuation pattern. Figures 15, 16and 17 demonstrate the evacuation of the patients categorized by patient type in each of the three hospitals.

Although VNICU, VPICU, and VICU patients have a higher threat risk and due to the high number of available patients of type 7 and 8, the optimal solution to decrease the overall risk was found to be by evacuating those patients first, followed by patients 1,2 and 3. Having a lower risk but almost similar patients count to the first three patient types, PICU, NICU and ICU patients were evacuated last. OA patients evacuated the hospital using the bus lane and thus left at the beginning of the evacuation process.



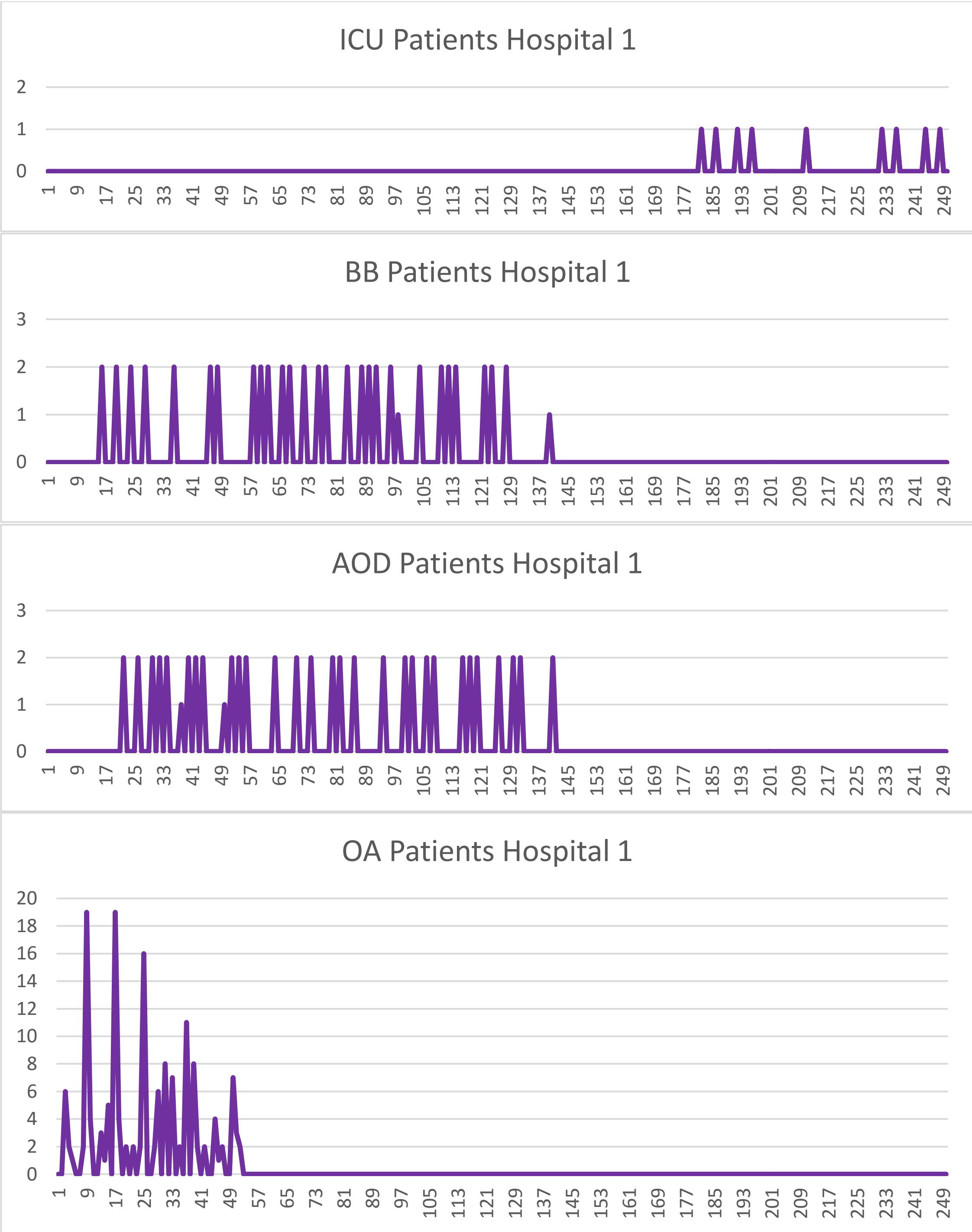
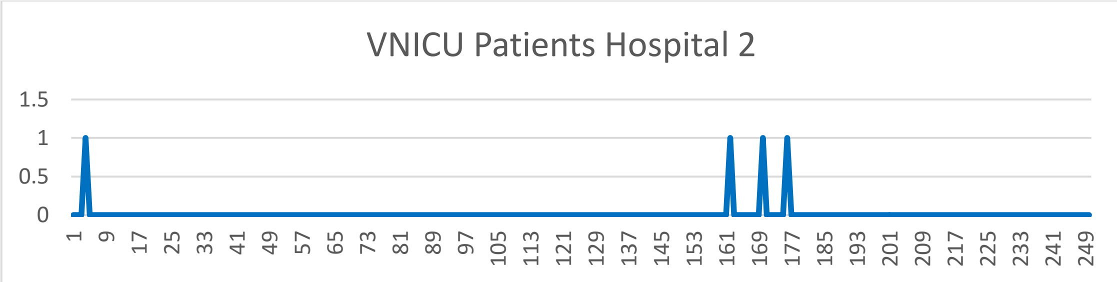
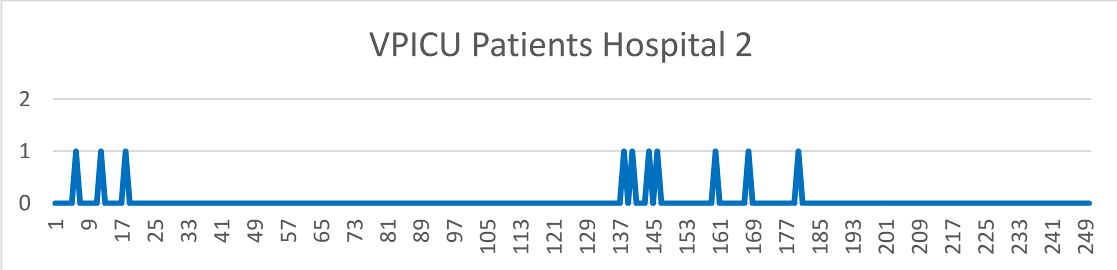
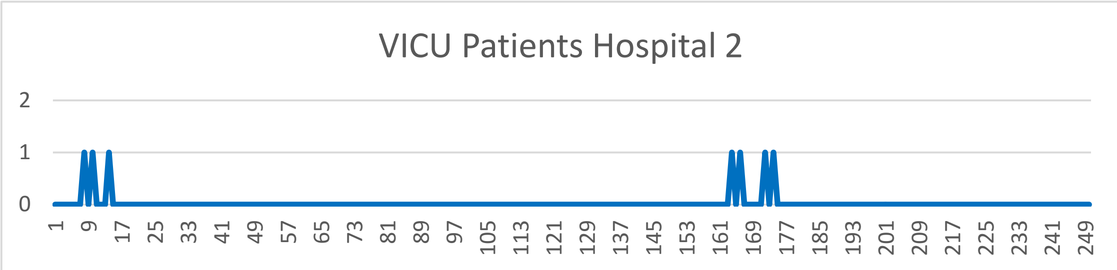
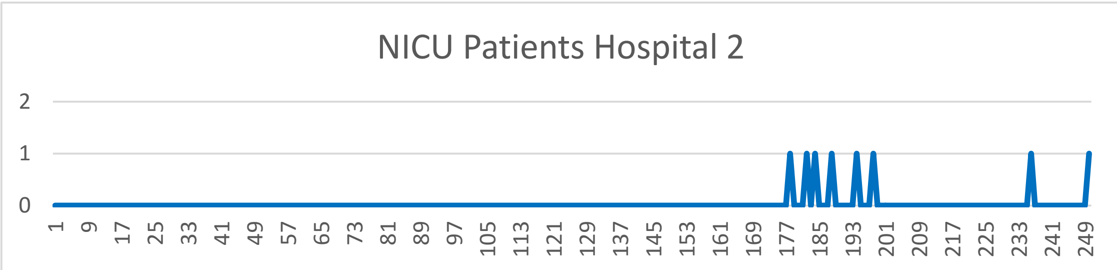


Figure 15: Patients evacuation pattern in hospital 1 by patient type


VNICU Patients Hospital 2
1.5
1
0.5
0
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


VPICU Patients Hospital 2
2
1
0
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


VICU Patients Hospital 2
2
1
0
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


NICU Patients Hospital 2
2
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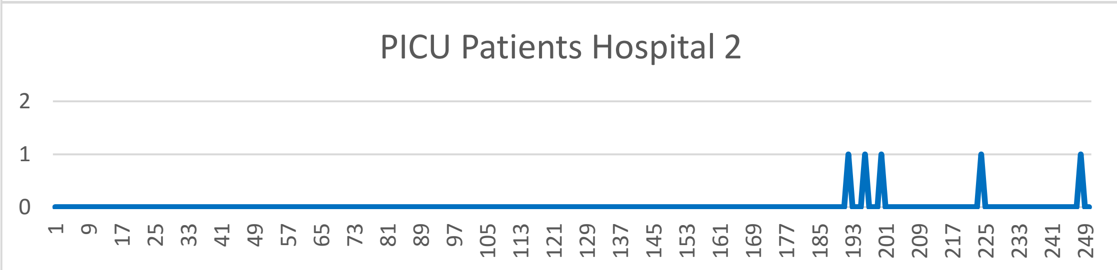
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


PICU Patients Hospital 2
2
1
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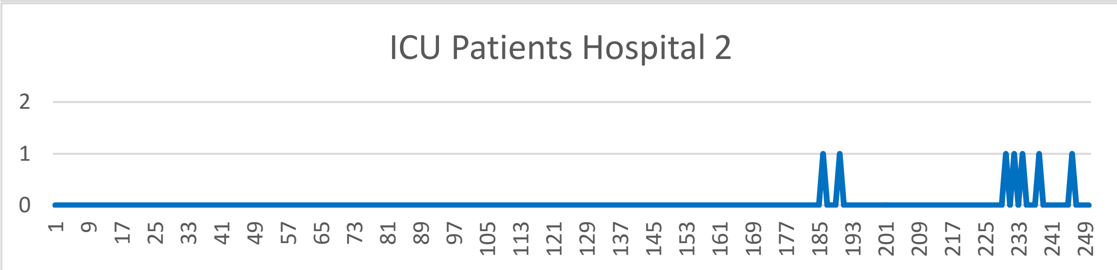
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


ICU Patients Hospital 2
2
1
0
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249

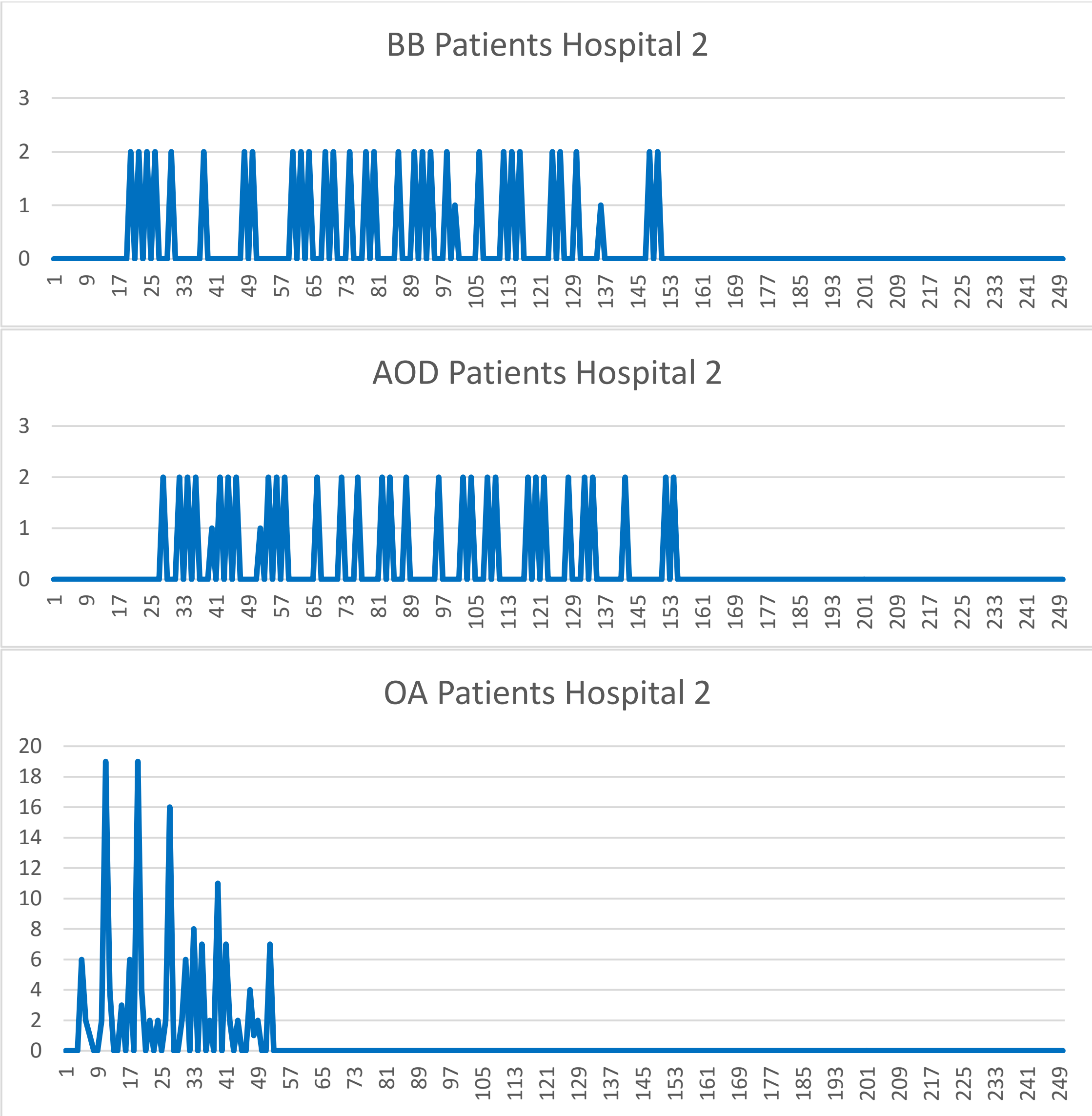
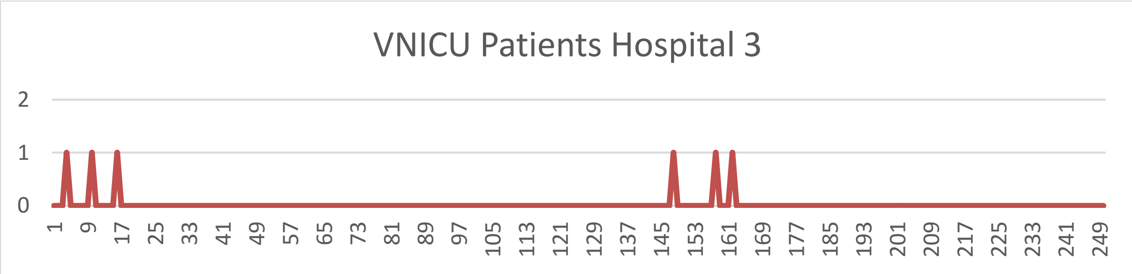
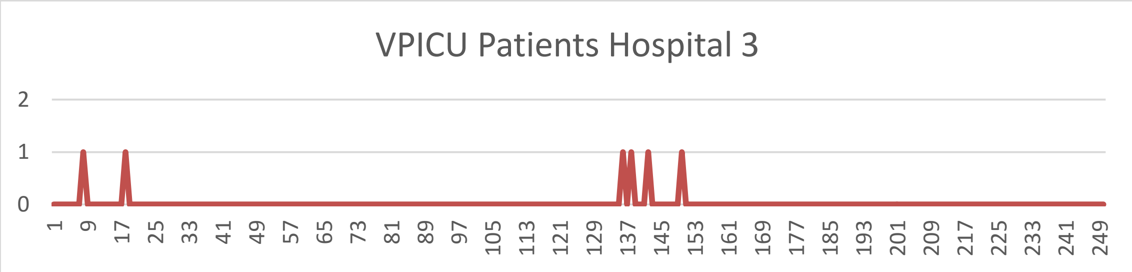
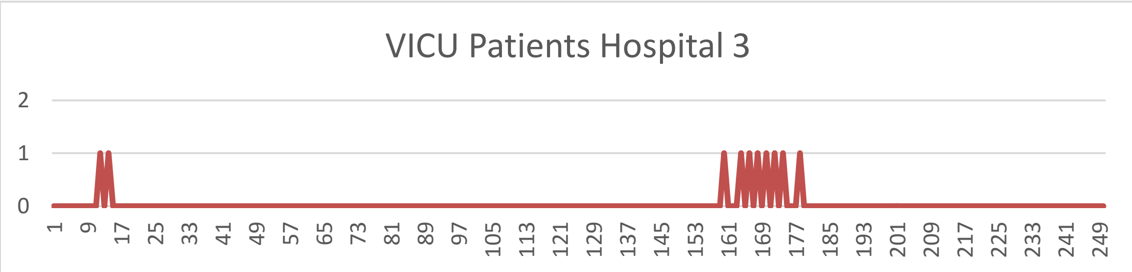


Figure 16: Patients evacuation pattern in hospital 2 by patient type


VNICU Patients Hospital 3
2
1
0
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


VPICU Patients Hospital 3
2
1
0
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


VICU Patients Hospital 3
2
1
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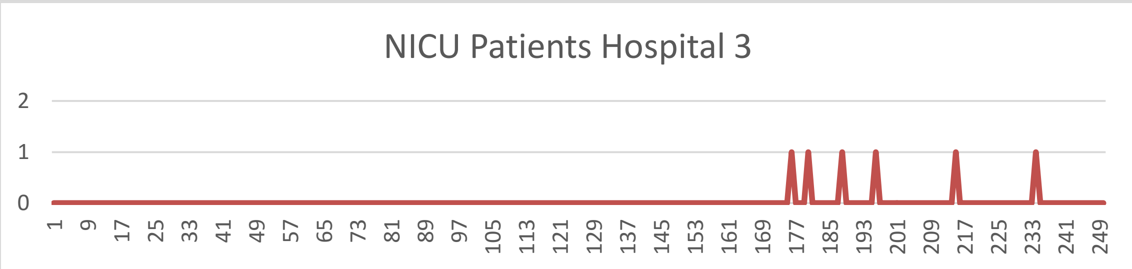
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


NICU Patients Hospital 3
2
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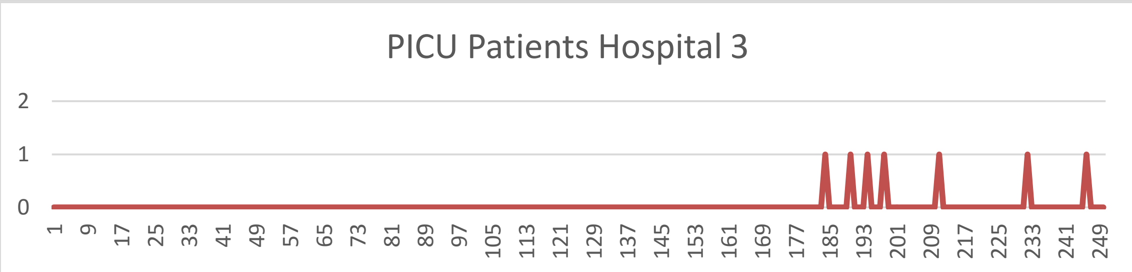
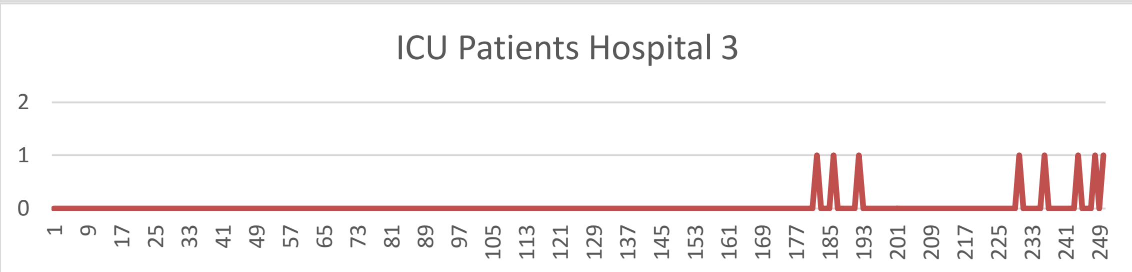
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


PICU Patients Hospital 3
2
1
0
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249


ICU Patients Hospital 3
2
1
0
1 9 17 25 33 41 49 57 65 73 81 89 97 105 113 121 129 137 145 153 161 169 177 185 193 201 209 217 225 233 241 249

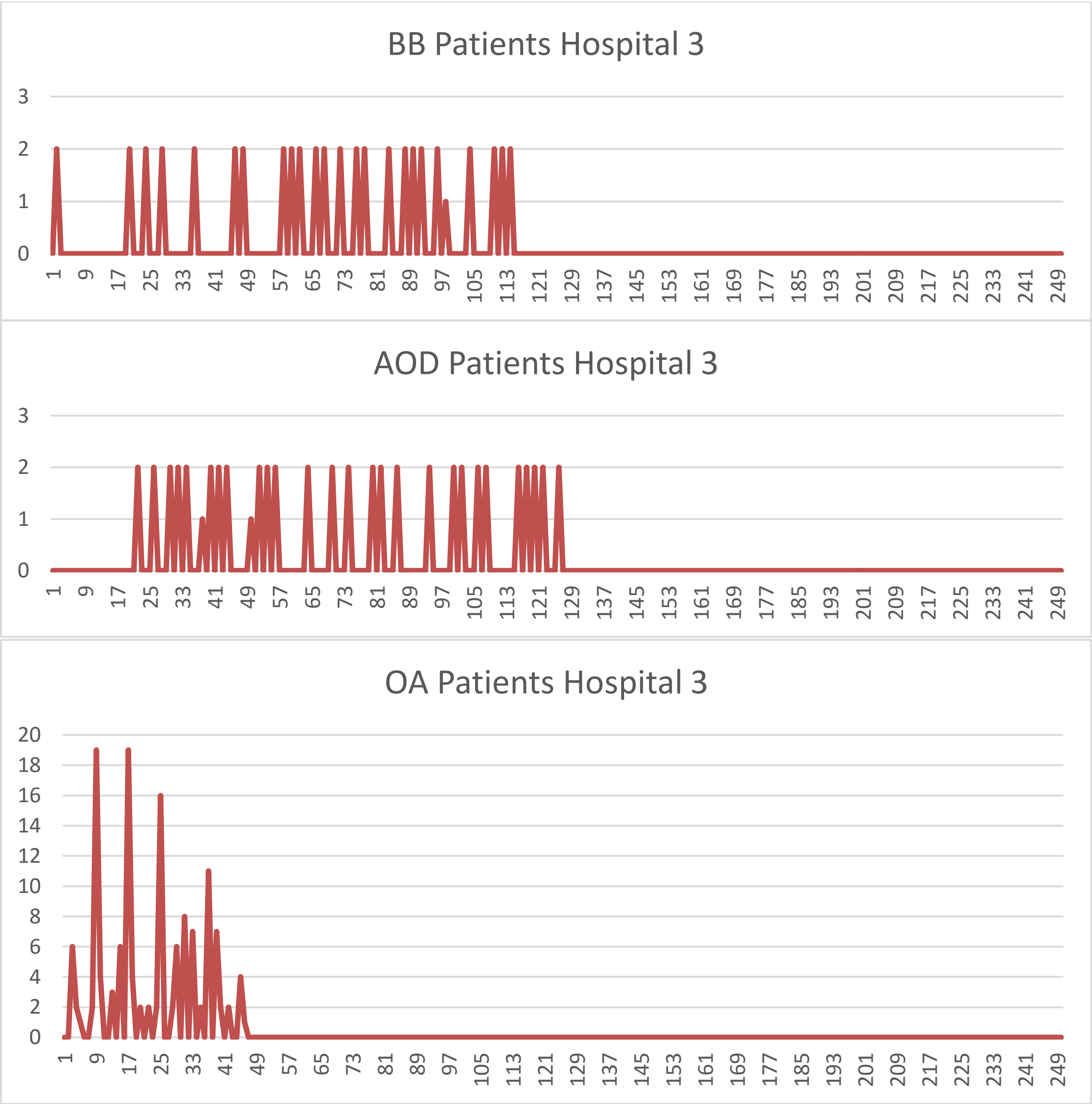


Figure 17: Patients evacuation pattern in hospital 3 by patient type

Finally, it is worth mentioning that between patients that have the same risk there was no preference in the evacuation order as they were evacuated in a diverse and mixed way depending mainly on the receiving beds.

- **Patients to Receiving hospitals:**

According to the mathematical model devised, patients were matched with a receiving hospital according to two criteria: the bed availability in the hospital and the traveling time between the receiving and evacuating hospitals. The results indicated that the beds were filled at first in receiving hospitals that were located relatively closer to the evacuating hospitals, which eventually yielded in having the beds being fully occupied in the closest hospitals; while the ones farthest are filled but don't essentially reach the maximum bed capacity. This conclusion can be deduced by comparing the bed availability in receiving hospitals in Table 15, with the number of beds occupied in each receiving hospital in Table 23.

- **Ambulance Lane Utilization**

In the original case, which states having one ambulance lane, the utilization for hospitals 1, 2 and 3 is 98%, 99% and 96% respectively which implies that the lane was not being fully utilized throughout the evacuation process and that the vehicles were the limiting resource. The lane was empty in some time intervals since there wasn't enough cars to cater for the needs of all the hospitals at once. This is presented by the minimum number of idle vehicles that was found. We can observe that there is 0 CCT, 0 ALS, and 19 BLS idle ambulances; this implies that we can reduce the BLS by 19 and not impact the solution, and that had there been more CCT and ALS the solution would have changed and the evacuation time would have been significantly lower. Although there is an excess number of BLS ambulances, all the patients that could be loaded onto this vehicle type (patients 7 and 8) were already evacuated prior to the time intervals where the ALS and CCT weren't available to load patients, thus the lanes were empty during these time intervals. Figure 18 demonstrates graphically the lane utilization with the evolution of time for the original instance in each evacuating hospital.

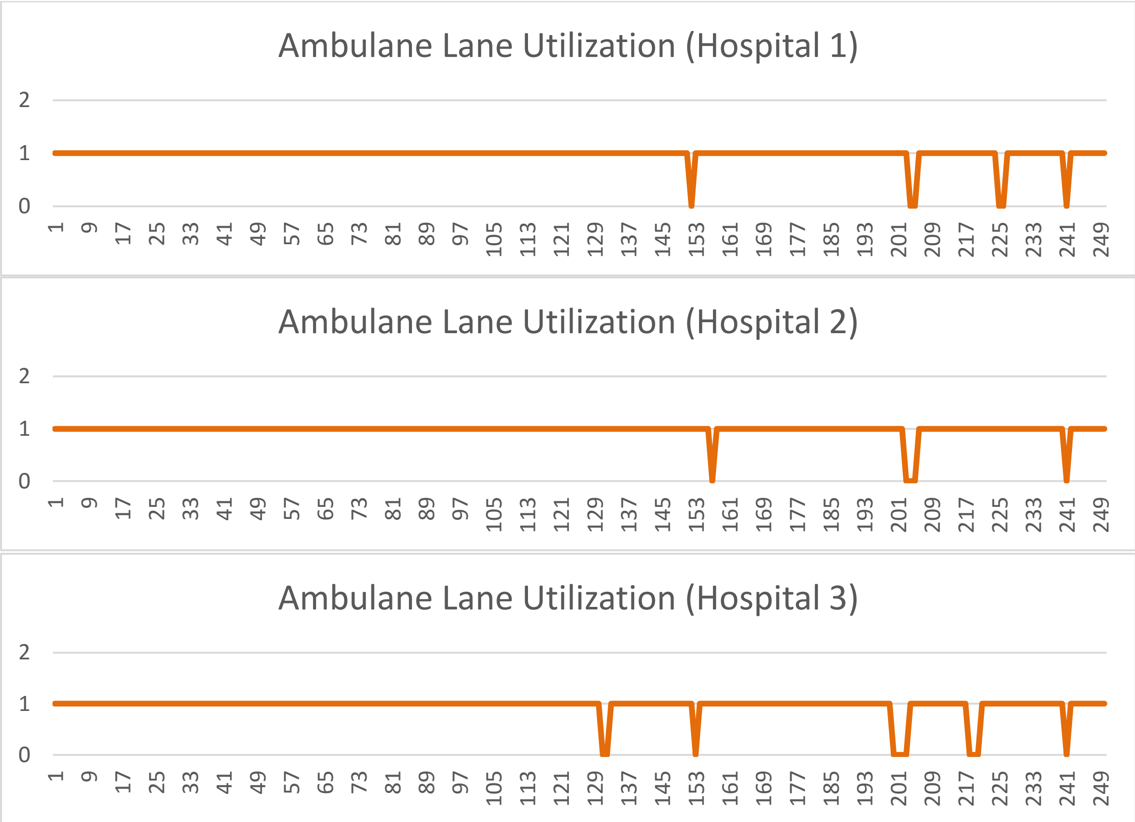


Figure 18: Ambulance lane utilization

In the second scenario where all three hospitals are assumed to have two ambulance lanes, the average utilization is 92%, which was comprised from three separate utilization factors for hospital 1, 2, and 3, which had a 93%, 94%, and 90% lane utilization respectively which also implies that at some time intervals, vehicles were not available to load patients. The number of idle ALS and CCT ambulances were found to be zero during some time intervals, while BLS had at least 16 idle vehicles throughout the process. The third case, which states having three ambulance lanes in each evacuating hospital, the average utilization is 81% with the same rationale as the other two scenarios. Table 24 is a summary of the results discussed, these results are also found in tables 21 and 22, in section 5.4.

Table 24: Minimum number of idle vehicle and average lane utilization in each scenario, with 10 minutes time intervals

	Minimum number of Idle vehicles			
Number of Ambulance Lanes	CCT	ALS	BLS	Average Ambulance Lane Utilization %
1 Lane	0	0	19	96%
2 Lanes	0	0	16	90%
3 Lanes	0	0	11	81%
Infinity	N/A	N/A	N/A	N/A

Upon increasing the number of lanes from one to two then to three lanes the evacuation time decreased but not by a significant amount since the lane capacity wasn't the limiting factor, moreover the utilization of the lanes decreased a lot especially in the three lanes case showing the extent to which the vehicles were a limiting resource. As the lanes increase the utilization will decrease exponentially due to the very low vehicle count and the evacuation time will decrease, however with a smaller change with respect to how much it decreased in previous scenarios. I.e. the evacuation time decreased by 14 hours moving from one lane to two lanes, but decreased by approximately 2 hours when the lanes were increased from two to three lanes. This is due to the fact that as the lane number is increasing they will become of less importance as a factor and the vehicle count becomes the absolute dominant factor and it will no longer effect evacuation time.

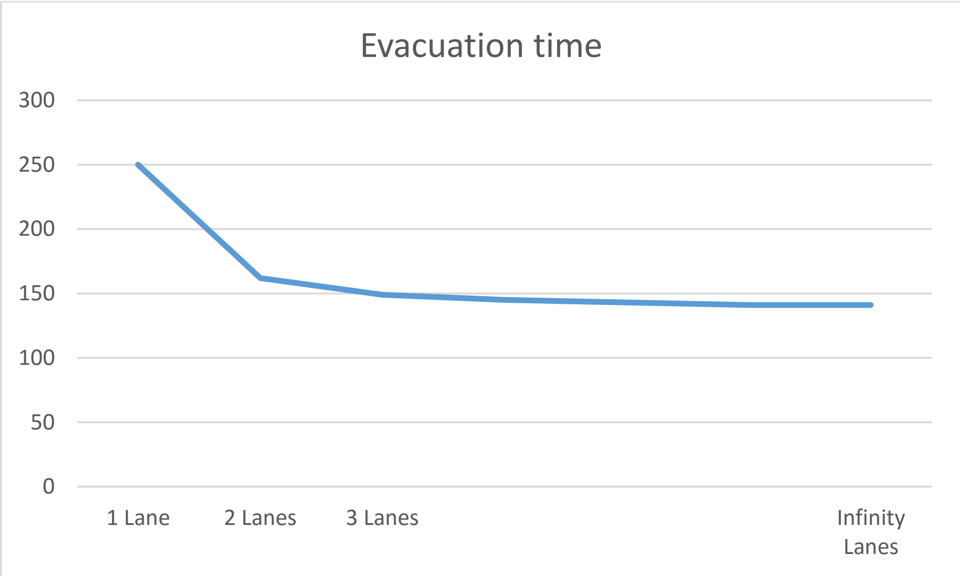


Figure 19: Evacuation time as a function of the number of lanes

As illustrated in figure 19 as the number of lanes increase the evacuation time will decrease but with a gentler slope, at some point adding lanes will not affect the evacuation time whatsoever.

- **Bus Lane Utilization**

In all the scenarios proposed in this instance (one, two, and three ambulance lanes) the utilization is not 100%, although there exists at least 1 idle bus out of the 10 available buses during the evacuation process in each of these setups. The reason behind not having a 100 % utilization, is not due to the scarcity of a resource, but due to the number of patients and their availability at the staging area throughout the evacuation process. The OA patients which were loaded onto buses were evacuated at the beginning of the evacuation process on a separate lane (bus lane) leaving no patients available to be loaded during the rest of the evacuation process and time intervals as shown in figure 15, 16, and 17. Hence leaving the bus lane idle during these time intervals. The utilization increased as the number of ambulance lanes were increased because the overall number of time intervals were reduced, decreasing by that the time intervals were the lane was idle. Figure 20 demonstrates the utilization of the bus lane in the original instance for each hospital. While table 25 summarizes the results discussed, these results are also found in tables 21, and 22, in section 5.4. Finally, as a conclusion the buses could be decreased by 1 without effecting the solution since there is at least an excess of 1 during the evacuation process.

Figure 20: Bus lane utilization graphs for the original instance in each hospital

Table 25: Minimum number of idle buses and average bus lane utilization in each scenario, with 10 minutes time intervals

Number of Ambulance Lanes	Average Bus Lane Utilization %	Minimum number of idle buses
1 Lane	15%	1
2 Lanes	16%	1
3 Lanes	17%	1
Infinity Lanes	N/A	N/A

- **Evacuation Team Utilization**

The teams are not being fully utilized since the patients are being moved to the staging area during the earliest time intervals, thus during the rest of the time intervals the teams are idle yielding a low utilization rate. As the number of time intervals is decreasing the utilization will increase, since the total number of time intervals where the teams are being utilized is almost the same but the overall number of time intervals is decreasing. Table 21 summarizes the average utilization of the teams in the three hospitals for the different ambulance lane setup. These results indicate that the evacuation teams are an excess resource and theoretically we can decrease this resource without affecting the solution. However decreasing the staff too much may affect the patient evacuation pattern which will yield a different solution and objective function.

- **Vehicle Utilization: Minimum Number of Idle Vehicles**

The minimum number of idle vehicles presented in table 22 in section 5.4. allowed us to infer that the vehicles were the limiting resources in our problem, increasing the vehicles will affect the solution drastically, it will decrease the evacuation time and the total risk that the patients are subjected to.

CHAPTER 6

CONCLUSION

In this research, we proposed two hospital-evacuation models, the first for single-hospital evacuation and the second for multi-hospitals evacuation. Realistic assumptions were deployed to develop the models, yet in a way that guarantees that these models mimicked their real-life counterparts. The objective of the models is to minimize both the cumulative threat and transportation risks imposed on the various patient types. The evacuation process is carried out while utilizing several resources, which inherently imposes a limitation on the process. The limiting resources incorporated in this model are: staff assisting patients out of the building, loading area capacity, vehicle fleet size and number of beds in receiving hospitals. These resources will be utilized in the following sequence, patients are moved from the evacuated hospital to the staging area by the staff, and then loaded onto the vehicles parked at the loading area (lane). Next, patients are moved to the receiving hospitals were they are situated based on their condition in their designated beds. Bearing in mind that the hospital evacuation and the patient's transportation to the receiving hospitals are dependent and that patients need assistance and medical care throughout this process, and the level of care and assistance they require is dependent on the patient's condition.

The resulting models are integer programs with a complex structure. These models were applied on two realistic cases. The first case study was based on the evacuation of a large regional hospital. The second case study will be based on the evacuation of several hospitals that reside within the same area. We then discuss some performance measures related to the models' objective functions and the optimal values simulated by the models.

In the first case, we discussed the excess and limiting resources in each scenario proposed. It was observed that the ambulance lane was the main limiting factor in the original instance which is when the hospital had one ambulance lane, while when more lanes were added the vehicle fleet size became the limiting factor specifically the ALS and CCT vehicle types. While the BLS and buses were in excess and in each scenario the number of vehicles belonging to these two types that could be eliminated without affecting the solution was inferred. Furthermore the different utilization factors calculated allowed us to conclude the other excess resources in the presented case and the leeway to eliminate them.

In the second case discussed, we were able to infer the excess and limiting factors in each scenario. The limiting factor was the CCT and ALS fleet size in all the scenarios, BLS and buses were in excess and in each scenario the number of vehicles belonging to these two types that could be eliminated without effecting the solution was inferred. The utilization factors were calculated which allowed us to deduce the excess recourses in the presented case and the leeway to eliminate them.

The extent of how much a resource can impose a limitation, and have an effect on the objective function, and evacuation procedure and time was illustrated in the two cases presented in this paper. In the two cases, it was observed that as the number of lanes increased, the evacuation time decreased but at a slower rate. This was highlighted in the second case in which increasing the number of lanes from three to infinity, only decreased the evacuation time by 80 minutes since the vehicles were the limiting factor and increasing the lanes did not affect the evacuation time as much as increasing the number of vehicles.

The models are user friendly they could be easily adjusted to include more or less patients, vehicles, lanes and bed counts and types. The number of receiving or evacuating hospitals could be altered easily as well. Although in the model proposed it is assumed that all patients must be evacuated, this could be easily improved to include only selective patient types depending on the threat type. This would be achieved by changing the set of patient types. Another alteration could be the evacuation constraint which enforces that all patients must be evacuated; however, in some cases, there could be a preset time that cannot be increased to accommodate all the patients. Thus the last constraint would be relaxed.

Finally, it is important to highlight the importance of the models presented in this paper by mentioning that there is no actual efficient and complete plan that allows hospitals to deal with the vast number of scenarios that can really occur. Hence, the dire need for a proper evacuation plan that can be performed under a vast number of scenarios that could take place. That plan can only be suggested by a suitable mathematical and optimization models. Keeping in mind that one possible extension of this study is to relax some of the assumptions in the model while keeping the problem tractable.

Future work could include increasing the tractability of the model by relaxing some of the integrality constraints due to its total unimodular matrix structure. Moreover a branch and price algorithm could be proposed to decrease the memory requirements for this model, which is especially helpful for big problems and cases.

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