The Use of Probabilistic Risk Functions and Linear Penalty Functions for Hospital Evacuation Planning

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ABSTRACT

In Bish et al. (2014), two approaches for the generation of hospital evacuation transportation plans were proposed: the minimization of the overall risk and the minimization of the evacuation duration. The resulting evacuation plans differ in terms of overall risk and duration, but also in the evacuation order of patients with different characteristics, the filling of hospital beds, and the assignments of the patients to the various vehicle types.

Due to the computational effort of the duration minimization, manipulations of the risk functions for the risk minimization approach were searched in this thesis such that the resulting evacuation plans approach the minimal duration without rules for the assignments of patients to vehicle types. It is possible to create risk functions such that the resulting plans have shorter durations than with the basic risk functions, but the overall risk increases and other properties of the plans change.

Furthermore, a new objective function was introduced in this thesis that minimizes an overall penalty function, where penalties are incurred for time intervals in which patients are at the evacuating hospital or being transported. The characteristics of the patients are considered by different weights in the penalty function. For the given problem instance, it is possible to choose penalty factors such that the overall risk is close to the minimal risk or to choose them such that the duration decreases. It is a simple approach with run times that are comparable to the risk minimization approach for the given problem instance.

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Chapter 1

Introduction

Hurricanes, earthquakes, and other threats can force hospitals to evacuate directly or on short notice, evacuation plans therefore have to be available or have to be generated quickly. The planning of evacuations is complex since many factors, such as the specific needs of patients, the available vehicles, the state of the hospital or the threat that causes the evacuation, have to be considered while aiming at the highest possible safety for the patients and a short duration. Due to the urgency that is likely to be linked to evacuation scenarios, hospitals are required to have evacuation plans, and the objectives of an evacuation have to be discussed and planned in advance of an emergency. The following literature summarizes the importance of evacuation planning by listing important insights from evacuations or emergencies and the planning for such events.

The earthquake in Northridge, California in 1994 led to numerous evacuations of hospitals and therefore provides important insights. Some evacuation scenarios are evaluated in Schultz et al. (2003). One interesting fact in terms of the organization is that five hospitals are reported to have evacuated the patients with the worst condition first while one hospital evacuated those patients with the best health first in order to evacuate a large number of patients in a short time interval. According to Schultz et al. (2003), the other five hospitals did not have to worry about immediate danger. The survey also gives an overview about various strategies to assign patients to vehicles, about who was in charge of organizing the transportation, about the specific reasons for the evacuations, about whether it was a complete evacuation and about the duration of the evacuation. Chavez and Binder (1996) describes the immediate effects of the earthquake on one specific hospital. The patients were moved out of the building in the order of fastest movement: patients who had to stay in a bed were moved last. For the transportation to receiving facilities the patients were sorted by decreasing criticality. Chavez and Binder (1996) states that it is essential for hospital evacuations that communication can be provided, that outside support is available and that the staff is prepared for emergencies like an evacuation.

Brown (2004) presents an emergency case caused by a power outage in a hospital without an evacuation that still provides valuable insights to an emergency situation and can help to improve emergency plans for the future. The available disaster plan did not anticipate all possible special cases and this emergency provided some ideas for improvements. One example are the elevators that were supposed to be at least partly available for patient evacuation. In reality, there was a time window where no elevator was working which would make the transportation of patients more complicated. Manion and Golden (2004) and Iserson (2013) focus on vertical evacuation which describes the movement of patients from one floor to another via stairs. Manion and Golden (2004) describes a drill where patients of the intensive care unit had to be moved four floors down via the staircase. The evacuation order assigned the least critical patients to be moved first, the drill was executed with a fire department and their equipment, without real patients and in order to provide multiple scenarios, the different actors playing the patients pretended to have different diseases. It was found that the vertical evacuation of intensive care unit patients requires extensive personnel and time. A more recent paper is Iserson (2013) that advocates another approach that uses mattresses and sheets for a vertical evacuation. This method has been used in several drills and it does not require special equipment from fire departments. Iserson (2013) also states that most hospitals do not have very specialized plans for such a scenario since the probability for those events is rather small.

Sexton et al. (2007) summarizes the evacuation of a hospital in Florida due to hurricane Rita in 2005. For the first time in the hospital's history, all patients were evacuated. Officials planning the evacuation had only three days to decide on a plan for this situation, that is, to prepare the patients and the equipment, and to prioritize patients for transportation. This allowed patients to be transported with those vehicles that suited their situation best. The most critical patients were evacuated first and paper copies of medical records were sent along with every patient. The authors mention many facts that were noticed in this evacuation that worked without a definite evacuation plan generated before the forecast of the hurricane. One fact was that communication devices did not work at all or not in all areas of the building, this problem was not anticipated before.

An evacuation due to a bomb threat in 1999 to a small rural hospital is described in Augustine and Schoettmer (2005). The number of patients was small and the intensive care unit was empty at that point of time which allowed for most patients to be transported to community buildings located in the surrounding area. Many patients could even be transported in a wheelchair because the evacuation radius was small and the weather and patient conditions were good enough. This specific case benefited from many fortunate factors and the overall problems were small. In general, generating evacuation plans for hospitals can be more complex which is addressed in Taaffe et al. (2005). The issues include the type of risk that occurs to staff and patients and the question whether and how this changes over time, resources and the probability of a threat. In addition, it can happen that the evacuation planners are not informed in a timely manner about the disaster and are therefore not able to provide all the possible help. Einav et al. (2004) summarizes how patients and their transportation to various facilities have been prioritized in 33 cases of mass casualties due to terror-activities. Einav et al. (2004) states that many urgent patients are rather transported to the closest hospital available instead of being transported to a trauma center where they could be treated better and that every hospital should therefore be prepared to receive patients that are classified as urgent.

One possible objective of a hospital evacuation plan is to minimize the duration of the evacuation given a set of available resources like vehicles, staff, and beds at other hospitals. Another approach, also presented in Bish et al. (2014), is to minimize the risk that arises from the situation that induced the evacuation itself as well as the risk associated with transporting a patient with certain risk characteristics to another hospital in a certain vehicle. In Bish et al. (2014), the results of these risk-minimizing strategies were compared to the strategies arising from duration-minimizing strategies with different constraints. The resulting evacuation plans differed considerably. The motivation for this thesis is to determine whether and under which circumstances both objectives can be reached simultaneously or how similar the properties of the generated evacuation plans can get.

One objective of this thesis is to further analyze the model presented in Bish et al. (2014) and to use the insights from the generated evacuation plans to identify the reasons for the differences in the plans. Based on this, the next objective is to identify situations or parameters that can cause both strategies to generate evacuation plans that converge to one plan. It is difficult to describe risks with certainty and this thesis focuses on only one case study, but it is important that the model has the potential to be realistic, which means that the situations or parameters used in the model have to be justified. Due to this uncertainty, it is also possible to exchange the probabilistic view with an approach that uses penalties. The overall objective of this thesis is to approximate a strategy that generates evacuation plans for hospitals under certain restrictions that have both a short duration and a reasonable risk.

The remainder of the thesis is organized as follows: the second chapter summarizes some main ideas in literature dealing with approaches to hospital evacuations. The third chapter of the thesis gives an overview about the objectives and procedures of the research and presents the models proposed in Bish et al. (2014) and a new objective function as well as a description of the problem instance. The fourth chapter presents the results that can be obtained with the different objective functions and ideas for modifications proposed in the third chapter. The last chapter gives a conclusion and an overview about future research.

Chapter 2

Literature Review about Hospital Evacuations

This chapter provides a brief overview about literature on modeling, optimization and simulation of evacuations that is helpful for a better understanding of the thesis.

The literature about evacuation procedures is broad due to the high relevance of this topic. Literature about evacuations in general and evacuations of hospitals in specific is not a recent topic, some articles like Leonard (1985) or Chalmet et al. (1982) have been published decades ago. There is, however, no conclusion about the best way to organize evacuations. Leonard (1985) summarizes information about evacuations and presents a collection of important points to consider when planning evacuations. This paper refers to the general case of the evacuation of a threatened area including special buildings that should have their own evacuation plans. The movement of persons like hospital patients is mentioned as a critical point during the evacuation of a whole region which is why disaster and evacuation plans need to consider them specifically.

This literature review overviews some papers about regional evacuations and about different approaches to hospital evacuation. Literature about regional evacuations can also be important for the planning of hospital evacuations.

Han et al. (2007) provides measures of effectiveness (MOEs) to determine the quality of an evacuation plan and shows that different objectives have to be considered. The four proposed measures here are the total evacuation time, the individual evacuation time which considers the time exposed to the threat, time-based risk which considers that the exposure risk might change over time, and the time-space-based risk which considers that the exposure risk might be different in different locations of the evacuating region. Tufekci and Kisko (1991) presents the Regional Evacuation Modeling System (REMS) for regional evacuations. The time needed for the evacuation can be computed via three different options: simulation, linear programming and network flow models since this system also uses time-expanded networks and is able to react to changes in the region like blocking of roads. It can also be used in cases of accidents that make parts of the region forbidden, that is, the threat that caused the evacuation makes certain regions so dangerous that they need to be left immediately.

The proposed simulation model in Franzese and Han (2002) incorporates different scenarios like missing information about blocking of routes and estimates possible evacuation routes, the evacuation time and evaluates possible bottlenecks. The authors intend to also incorporate real-time information into the simulation model. The authors of Ng and Waller (2010) consider that the number of people to be evacuated and the resources in terms of roads may not be known and even a probability distribution might not be available. Their approach leads to more conservative evacuation plans with longer evacuation times. Those plans are more reliable in that the reality is not likely to perform worse than the scenario used for creation of the evacuation plan. The identification of transportation risks during evacuations due to a nuclear power plant incident is approached in Bastien et al. (1985). The authors determine the average risk to get involved in a traffic accident that leads to death or an injury under normal driving conditions and compare those values to the actual values that were found in some real evacuations. It is concluded that the values for normal driving conditions overestimate the risks that occur during an evacuation. The authors propose the different driving conditions and the different psychological situation as possible reasons.
Another aspect to consider when evaluating evacuation plans of regions are the assumptions that were made in order to generate the plans. Auf der Heide (2006) discusses some common assumptions in situations of disasters and whether those are realistic. While the paper focuses on the evacuation of the disaster location, some of the mentioned aspects are related to the behavior at the hospitals involved. According to Auf der Heide (2006), it often occurs that most of the casualties of the disaster are transported to the same hospital. This can also affect the evacuation of a hospital if the number of beds at a receiving hospital is smaller than assumed.

Mills et al. was not published yet and focuses on the distribution of patients to hospitals from multiple but close locations where the same catastrophe or disaster took place and caused larger numbers of casualties. In this paper, a dynamic rule is searched that considers both changes in the congestion at the different hospitals as well as a limitation on the number of available vehicles and is mainly based on queuing theory. Two heuristics were developed to determine where a casualty should be sent instead of just sending all casualties to the closest facility available from a particular location. In simulations conducted by Mills et al., those heuristics performed well for different scenarios.

There are different aspects to evacuations of hospitals or buildings in general. The model presented in Bish et al. (2014) focuses on the transportation of patients from the evacuating building to the receiving hospitals, but a very common way is to focus on the evacuation within the building which is restricted by hallways, stairs and obstacles like the threat in the building that made the evacuation necessary. Both perspectives are critical and relevant to the whole evacuation process but are mostly examined separately in literature.

Hamacher and Tjandra (2001) presents an overview about approaches to evacuations inside the buildings and divide those at first into macroscopic and microscopic approaches. The macroscopic perspective is mainly based on optimization approaches whereas microscopic models rather use simulation approaches. The literature offers both approaches as well as general descriptions of problems.

Wabo et al. (2012) use exemplary hospitals in Sweden and state that the evacuation plans within the general framework of disaster plans are sometimes not existent and mostly not drilled so that the actual situation is not practiced in hospitals. The authors advocate better evacuation plans in all hospitals that are drilled on a regular basis in order to familiarize the staff with problematic situations. Johnson (2006) in contrast notes that drills can deteriorate the health of patients and interfere with the activities in a hospital and therefore presents a simulation for evacuation processes of buildings like hospitals. Since this paper focuses on the process inside of the building, the risks that have to be assessed are possible causes for evacuations and their probabilities and impacts. Experiences from the past can be used to identify possible problems that have to be considered in an evacuation plan. The developed Glasgow Evacuation Simulator (GES) incorporates randomness in the behavior of individual persons, uses existing 3D-models of the building and various characteristics of patients, and can be used to evaluate different evacuation scenarios.

Chalmet et al. (1982) studies the evacuation process inside of buildings like office buildings in order to find bottlenecks during the evacuation. The authors model the building as a time-expanded transshipment network with different parts of the buildings including elevators, stairs and office space with their different characteristics like capacities. The results of this model were compared with a drill evacuation in the building that was used as an example for the model. The use of models can help to identify where evacuations could work better. One important proof used was that in time-expanded networks some objectives like the average time to leave the building on the one hand and the minimization of the total evacuation time on the other hand are always reached simultaneously. This was shown in Jarvis and Ratliff (1982) which was inspired by the research of Chalmet et al. (1982) and published at the same time. Choi et al. (1988) refer to the general structure of a building generated in Chalmet et al. (1982) and note that capacities should not be assumed to be constant. Instead, the capacity on arcs from one place in the building to another is depending on the density of the population in the originating node and is implemented by the use of side constraints to the model. Evacuation strategies of such models are determined in terms of different questions like maximum number of persons who can be evacuated in a given time or minimal time of the last person leaving the building.

Another paper dealing with evacuations inside of buildings with multiple exits is Pursals and Garzón (2009) which uses the minimization of the duration as objective. The proposed algorithm computes the number of people to leave the building via a certain exit with the help of information about the characteristics of the exit as well as density functions that are generated by the number of people using the given exit.

Golmohammadi and Shimshak (2011) presents a model to simulate the processes on the inside of a hospital during an evacuation. Resources are assigned to patients according to their categorization and bottlenecks like the number of elevators can be considered in this model. In general, the objective is to evacuate as many patients as possible and due to the assumption that less critical patients are easier to evacuate and require a shorter preparation, those are evacuated first. Chen and Miller-Hooks (2008) proposes a model that provides the evacuees in building evacuations with information about how to proceed. The model considers capacities and travel times on arcs to change over time and aims at sending all people who start the evacuation at the same time and place along the same route. This refers to the fact that everything else would not make sense to evacuees in such a situation.

A paper on the simulation of the evacuation of hospitals without a focus on the interior is Taaffe et al. (2006). The proposed model uses discrete-event simulation for hospital evacuations due to hurricanes and incorporates stochastic characteristics as well as limitations on resources. Updates on forecasts, new patients arriving and patients being released from the hospital are considered. The patients are categorized in different care levels and are assigned to transportation vehicles according to the category. The authors determine how changes in parameters like the number of patients, available beds or transportation vehicles affect the results of the evacuation plan. A very recent approach is presented by Tayfur and Taaffe (2009b) which proposes a deterministic approach to minimize costs while a specific evacuation-time has to be met. The model used in Tayfur and Taaffe (2009b) considers restrictions on staff, vehicles and equipment as well as different patient types. The use of vehicles and the assignment of staff contribute to the costs of the evacuation, not evacuating patients causes a penalty cost in the model. Exact optimal solutions were only found in some cases, all cases were solved by removing the integer restrictions. For a heuristic solution, a local search around the rounded solution from the relaxed model was conducted. This model was used in Tayfur and Taaffe (2009a) for a simulation of evacuations since drills of evacuations are not common in hospitals. Congestion on the roads is considered to be time-changing as more buildings than the hospitals have to be evacuated. The authors conclude that a longer allowed evacuation time tends to decrease the costs and state that, depending on the situation, the start of the evacuation time can influence the results. Another paper that focuses on how to prioritize patients if resources may not allow for a complete evacuation is Childers et al. (2009) which is one step of the research for Childers et al. (2014). Two types of patients are assumed with different probabilities to survive the evacuation, to die while waiting for the evacuation and to die during the evacuation. Simulation was used to obtain information about the evacuation plans for different scenarios and different possible evacuation policies. Childers et al. (2009) state that the optimal evacuation policies do also consider the less critical patient type, some optimal policies start with the noncritical patients, switch to the critical patients, and switch back once those are completely evacuated. Childers et al. (2014) is one of currently three articles that refer to Bish et al. (2014) and focuses on the prioritization of patients in different categories to the evacuation-process outside of the hospital. In order to determine the effects of different prioritization strategies of patients, it is assumed that enough transportation vehicles are available for an evacuation. The authors assume a scenario with two patient types and different parameters like the rate at which patients can be evacuated, the probability that a patient survives the transport, and the rate at which patients of a given group die while waiting for their evacuation. The strategies available for scheduling the patients are to either prioritize one patient group before the other or to switch from one group to the other and then back. The conclusion of Childers et al. (2014) is that the number of parameter-sets where a switching-rule gives the best results increases with increasing problem size. If more than one evacuation team is available, it is advantageous to apply the same strategy to both teams. Another discovery was that the best evacuation prioritization strategy can be estimated by a ratio that is computed with the parameters in the given situation. This paper, however, does not consider vehicles or beds at receiving hospitals. It somehow takes risk into consideration as it needs information about the rates of death during the time of waiting and the chance of surviving an evacuation. A deterioration of the state of the patient is not considered in any form in this model.

Chapter 3

Modeling Framework, Problem Instance, and Objectives

The purpose of this chapter is to introduce the modeling framework and objectives for the generation of hospital evacuation transportation. The first section presents the HETM for risk-minimizing and duration-minimizing strategies from Bish et al. (2014) in the current version. The second section presents a general and abstract introduction to the hospital evacuation transportation model along with the problem instance used in this thesis. A new objective function which uses penalties is introduced in the third section. The fourth section discusses the objectives of the thesis and concludes the chapter with the main ideas that are to be pursued.

3.1 Background: Hospital Evacuation Transportation Model

This section provides an overview of the Hospital Evacuation Transportation Model (HETM) (see Bish et al. (2014)) that is used in this thesis. The model itself and some assumptions are described as well as the model for a duration minimization. The model formulations and the parameters are from Bish et al. (2014) which also gives more detailed explanations of the models. The model formulations are described here as a necessary background.

The HETM provides an approach to hospital evacuation planning that uses estimates of the risk in the given situation and provides an evacuation plan that minimizes the overall risk of the evacuation. The overall risk of the evacuation is composed of two parts: the threat risk that arises in the hospital itself for the patient until the evacuation and the transportation risk. The transportation risk depends on the vehicle type the patient of a given risk group is transported in and on the time it takes to reach the receiving hospitals. That is, all patients have a smaller transportation risk in the best equipped vehicles and a higher risk if they are transported in a bus. In addition, the more critical patients have a higher transportation risk than less critical patients.

Three different variations of a duration-minimization were used that regulate the assignment of patients to the vehicles. One approach is to specifically assign patient types to vehicle types, a second approach allows to upgrade patients to a better vehicle than the assigned vehicle type, and the last one does not use any restrictions for the assignment of patients to vehicles. This last approach results in the shortest duration due to its flexibility.

The version of the HETM used in this thesis makes the following assumptions:

- All patients have to be evacuated from the hospital and the process inside of the building is not limiting the evacuation transportation.
- The time to be used as a measure for the duration of the evacuation is the time interval in which the last patient is delivered to a receiving hospital.
- The number of available beds in the receiving hospitals as well as the number of available vehicles for transportation are fix and known.
- The risks, both transportation and threat risk, were not assessed empirically but invented for the purpose of the model and the belonging research and are hypothetical. The same holds true for the number of patients in the various categories, the number of receiving hospitals, their distances from the evacuating hospital, the numbers of available beds in the receiving hospitals, and the types and numbers of evacuation vehicles.
- The route time from the evacuating hospital to the receiving hospitals is constant and not subject to changes due to congestion.

The decision variables in the HETM are x_{ijkt}, which describes how many patients of the type j are transported to a hospital i in a vehicle of type k starting at a time interval t and y_{ikt}, which describes the number of vehicles of type k that are used starting at a time interval t to transport patients to hospital i. The objective function is given by

$$\text{Minimize } \sum_{i=1}^{H}\sum_{j=1}^{P}\sum_{k=1}^{V}\sum_{t=1}^{T} R_{ijkt}x_{ijkt} + \sum_{j=1}^{P} \Lambda_{jT}(W_j - \sum_{i=1}^{H}\sum_{k=1}^{V}\sum_{t=1}^{T} x_{ijkt}), \tag{3.1}$$

where R_{ijkt} is the overall risk and is computed as

$$R_{ijkt} = 1 - (1 - \Lambda_{j(t-1)})(1 - \Theta_{ijk}),\ \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V, t = 1, ..., T, \tag{3.2}$$

where Λ is the cumulative threat risk that describes the exposure of the patient to the threat and is computed as

$$\Lambda_{jt} = 1 - \prod_{f=1}^{t}(1 - \alpha_{jf}),\ \forall\ j = 1, ..., P, t = 1, ..., T \tag{3.3}$$

with α_{jt} as a probabilistic risk for a patient of type j in time interval t.

Θ is the cumulative transportation risk that incorporates the loading and unloading time γ_k of the patient as well as the transport time τ_i, where Θ is computed as

$$\Theta_{ijk} = 1 - (1 - \beta_{jk})^{(\tau_i + 2\gamma_k)},\ \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V. \tag{3.4}$$

The constraints in the HETM ensure that all patients W_j are evacuated, that vehicles do not transport more patients than their capacity C_k allows for, that the number of patients of a given type transported to a hospital does not exceed the number of available beds B_{ij} for this type, that the number of vehicles used does not exceed the number of available vehicles, that the hospitals vehicle loading capacity is not violated, and that the decision variables have integer values.

$$\sum_{i=1}^{H}\sum_{k=1}^{V}\sum_{t=1}^{T} x_{ijkt} = W_j,\ \forall\ j = 1, ..., P \tag{3.5}$$

$$\sum_{j=1}^{P} x_{ijkt} \leq C_k y_{ikt},\ \forall\ i = 1, ..., H, k = 1, ..., V, t = 1, ..., T \tag{3.6}$$

$$\sum_{i=1}^{H} y_{ikt} + \sum_{i=1}^{H} \sum_{f=1}^{min(2(\gamma_k+\tau_i)-1,t)} y_{ik(t-f)} \leq N_{kt}, \forall\ k = 1, ..., V, t = 1, ..., T \tag{3.7}$$

$$\sum_{k=1}^{V} \sum_{t=1}^{T} x_{ijkt} \leq B_{ij}, \forall\ i = 1, ..., H, j = 1, ..., P \tag{3.8}$$

$$\sum_{i=1}^{H} \sum_{k=1}^{V} L_k y_{ikt} \leq L, \forall\ t = 1, ..., T \tag{3.9}$$

$$x_{ijkt} \geq 0, \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V, t = 1, ..., T \tag{3.10}$$

$$y_{ikt} \geq 0 \text{ and integer}, \forall\ i = 1, ..., H, k = 1, ..., V, t = 1, ..., T \tag{3.11}$$

The objective of the duration minimization is given by

$$\text{Minimize } E, \tag{3.12}$$

where E is the time interval of the last delivery of a patient to a receiving hospital. In order for this formulation to work, the following constraints are necessary in addition to the ones from above. Here, b_{ikt} is a binary variable necessary for determining whether patients are transported in a time interval.

$$\frac{y_{ikt}}{L} \leq b_{ikt}, \forall\ i = 1, ..., H, k = 1, ..., V, t = 1, ..., T \tag{3.13}$$

$$b_{ikt}(t + \tau_i + \gamma_k) \leq E, \forall\ i = 1, ..., H, k = 1, ..., V, t = 1, ..., T \tag{3.14}$$

$$b_{ikt} \text{ binary}, \forall\ i = 1, ..., H, k = 1, ..., V, t = 1, ..., T \tag{3.15}$$

$$E \geq 0 \tag{3.16}$$

Bish et al. (2014) shows that the duration of an evacuation plan created with the duration-minimizing strategy without rules for the assignments of patient types to vehicle types is shorter while having a higher risk. For the given problem size, the creation of an evacuation plan based on a duration-minimizing strategy requires more computational effort than plans based on a risk-minimizing approach although the difference depends on the restrictions and assumptions made for the duration-minimizing approach.

3.2 General Remarks and Problem Instance

In many cases of optimization models, the model and the specific problem instance are separated and the model can be used to solve different instances. In Bish et al. (2014), the model is either the one to minimize the overall risk or the one to minimize the duration. The instance is described by the patient categories and the number of patients in each category, the hospitals, the route time, and the available beds as well as the vehicle types and the number of available vehicles in the different time intervals. Both the parameters of the threat risk in the hospital and the travel risk are not that easily to be categorized to either the model or the instance. On the one hand, those parameters describe the concrete situation of the evacuation. On the other hand, it is not possible to determine the exact values for those threat risks and it is not even always possible to determine whether the threat risk is to increase with time. As shown in Bish et al. (2014), the model for risk minimization with the arbitrary assumptions about the threat risk and the transportation risks results in good evacuation transportation plans with a small risk. The model for duration minimization with no restrictions on how patients are assigned to vehicles, however, generates evacuation plans with shorter durations but with a higher overall risk that might not have desirable properties in that critical patients are as likely to be assigned to the best equipped vehicle type than to the worst equipped vehicle type.

The HETM with the risk minimization objective function considers two risks. The first part of the objective is to minimize the threat risk that is caused by the stay of patients in the evacuating hospitals. If it was possible to evacuate all patients in the first time interval, the threat risk could be eliminated as no patient would be exposed to any risk. The second part of the objective is to minimize the risks caused by the transportation. This risk cannot be eliminated as all patients must be transported to a receiving hospital but it would be minimal if all patients could be transported to the closest hospital in the best type of evacuation vehicle. The HETM considers three categories of resources that limit the solution, which are the number of vehicles, the number of available beds in the receiving hospitals, and the loading space at the evacuating hospital. Even if there were an unlimited number of vehicles of the best type, the loading area would restrict the evacuation of patients. If there were an unlimited number of vehicles available, the route time to the hospitals would not be critical and it should be assumed that the most critical patients are evacuated first and that the beds in the closest hospitals are filled first. Since, however, the number of vehicles is not unlimited and there are only few vehicles of the best vehicle type, there is a trade-off between the time patients have to stay in the evacuating hospital and the transportation in a vehicle that might not be optimal and that is not available for the loading and routing time.

The model for the minimization of the duration does not consider the transportation as a risk and only factors in that the time the vehicle is not available for the transportation of other patients depends on the routing time. The threat risk is also not incorporated as the duration minimization approach aims at minimizing the last delivery of a patient at the receiving hospital which depends on the departure at the evacuating hospital, the loading time, and the routing time. This model is therefore somehow a penalty approach in that it only counts time intervals until the delivery where all time intervals count the same. This approach is too simplified for a real evacuation planning manager as it does not differentiate between the patient types in terms of their risk characterizations.

In Bish et al. (2014), three threat risk scenarios were implemented that impact the various patient categories in different ways. The first scenario assumes the threat risk to be equal for every single time interval, the second describes a linear increase for the single time intervals, while the last scenario shows an exponential increase in the threat risk for the time intervals. The threat risks impact the patients in different ways: more critical patients in the first risk group experience higher threat risks in every threat risk scenario than less critical patients in the third risk group. The risk parameters for the threat in the hospital and the transportation in a vehicle cannot be assessed realistically and those used in the case study in Bish et al. (2014) and in this thesis are hypothetical. The overall risks that are used as a measure to evaluate the generated evacuation transportation plans are therefore an artificial construct.

The problem instance from Bish et al. (2014) was adapted for the purpose of this thesis. The number of patients in the three patient categories (which have different risk characteristics) are given in Table 3.1, 240 patients have to be evacuated in total. The patients in the risk group 1 are the most critical and have higher probabilities of experiencing a deterioration of their state, the patients in risk group 3 are the least critical patients and patients from the middle risk group have risks that are between those of the most critical patients and those of the least critical patients. The terms risk group and patient type can be used equivalently here as every patient type has its own risk group. In general, though, it is possible to use the model for larger problem instances where multiple patient types share the same risk characteristics.

Table 3.1: Numbers of patients of different patient types

Patient type	Patient type 1	Patient type 2	Patient type 3	Total
Number of patients	50	129	61	240

The number of hospitals and their distances to the evacuating hospital are presented in Table 3.2 along with the numbers of available beds that were adapted from Bish et al. (2014).

Table 3.2: Hospitals: route times and available beds

Hospital	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Route time	8	7	4	9	6	3	14	3	11	8	6	8	10	2	9
Beds pat. type 1	8	4	6	3	5	0	7	12	62	8	14	18	2	2	4
Beds pat. type 2	14	10	6	4	2	0	10	19	77	60	8	10	10	5	18
Beds pat. type 3	6	3	2	1	10	3	5	4	24	24	2	6	3	3	26

In addition, both a scenario with buses as well as a scenario without them were tested. In the first time intervals, no buses are available and only some ambulances of both types, but the numbers of available vehicles increase until the maximum numbers of vehicles over the 150 time intervals of 14 for both ambulance types and 2 for buses are reached after 7 time intervals. For the comparisons of new scenarios with the basic results, only the most flexible variation of the duration minimization that does not use any restrictions for the assignment of patients to vehicles was used since it offers the best results in terms of duration. The other variations are also tested and only compared to the duration minimization without restrictions.

The most important results to consider are the time the last patient leaves the hospital and the time the last patient reaches a receiving hospital. It is, however, also interesting to observe how the patients of the various patient categories are assigned to the vehicles and in which order the available beds in the hospitals are filled.

The objective in the risk-minimization is to minimize the overall risk that is compounded of the transportation risk and the threat risk in the evacuating hospital. Since the travel risk depends on the assignment of a patient of a certain risk category to a certain vehicle, it was expected that a risk-minimizing strategy considers those differences and aims at a certain differentiation, that is, transporting the most critical patients in the best equipped vehicles. At the same time, the threat risk at the hospital is higher for more critical patients, so the risk-minimization is also expected to prioritize patient types for the transport to the receiving hospitals. The cumulative threat risks for the scenario of a constant threat at the evacuating hospital is shown in Figure 3.1 for the three risk groups.

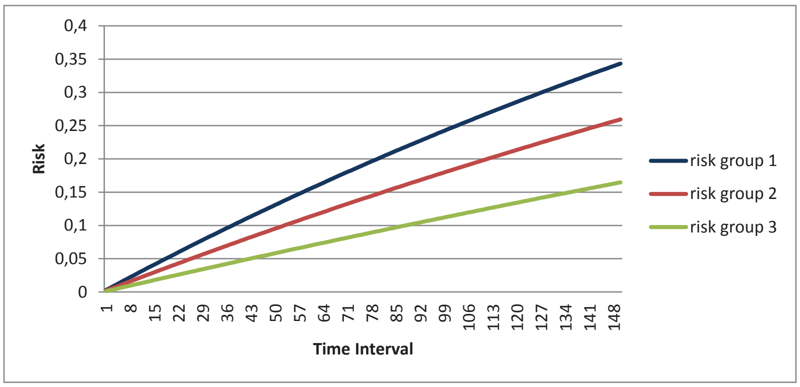

Figure 3.1: Cumulative threat risk for a scenario of a constant threat

Table 3.3 presents the travel risks for the three different risk groups that are used together with the load time and the route time to the receiving hospital to compute the transportation risk for a certain patient that is being transported to a receiving hospital in a certain vehicle. These values are from Bish et al. (2014).

Table 3.3: Travel risks for patient types and vehicle types

	ALS (vehicle type 1)	BLS (vehicle type 2)	Bus (vehicle type 3)
Patient type 1	0.001	0.002	0.01
Patient type 2	0.0001	0.0002	0.0005
Patient type 3	0.00005	0.00005	0.0001

3.3 Objective Function using Penalties

One important insight from Schultz et al. (2003) is that there are different incentives in evacuation situations. While in some situations transporting patients as fast as possible is desirable, in other situations the transportation safety, that is, using the best possible transportation type, might be more important. In the HETM, the internal movements of patients from their care location to the staging area is ignored, which is an appropriate assumption only if there are sufficient resources for this important step in the overall evacuation. If this is not the case, then this resource, and the movement times of different patient types should be considered as critical patients or patients from further wards might utilize the resources for internal transportation more than other patients. Those transportation processes inside of the evacuating hospital are not considered in the model used for this thesis, but are considered in ongoing research. The computational efforts are even higher if both the inside process and the transportation to receiving hospitals have to be considered. One possible advantage of a penalty approach might be to reduce the computational effort for further applications of the modeling framework.

The basic idea here is the same as in the approach with probabilistic risks as the stay in the evacuating hospital on one side and the transportation to a receiving hospital on the other side are separated and then combined in one measure that is to be minimized for the whole evacuation transportation process. The overall penalty is combined as the sum of the transportation penalty and the penalty caused by patients staying in the evacuating hospital until they are transported.

The transportation penalty is computed as a product of the transportation duration for a patient and a factor φ_{jk} that depends on the vehicle type k and the patient type j. The transportation duration consists of the route time to the receiving hospital i and the loading time of the patient into the transportation vehicle which is depending on the vehicle type k and counted twice as the patient is loaded into the vehicle and then out of it again. The transportation penalty for a patient of type j in a vehicle of type k to receiving hospital i is calculated as follows:

$$\Phi_{ijk} = \varphi_{jk} \cdot (\tau_i + 2 \cdot \gamma_k), \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V, \tag{3.17}$$

where the penalty for the patients staying in the hospital until their transportation is computed as product of the duration of the stay and a factor μ_j that is depending on the patient type j. Penalties for the stay of patients of type j who are staying in the hospital until time interval $t-1$ (as the patient starts the loading process into the vehicle in time interval t) are computed as

$$M_{jt} = \mu_j \cdot (t-1), \forall\ j = 1, ..., P, t = 1, ..., T. \tag{3.18}$$

Those two separate penalties can then be added to a penalty for evacuating a patient of type j in time interval t in a vehicle of type k to the receiving hospital i. This penalty is computed as

$$\Omega_{ijkt} = \Phi_{ijk} + M_{jt}, \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V, t = 1, ..., T. \tag{3.19}$$

The new objective function is formulated as

$$\text{Minimize} \sum_{i=1}^{H}\sum_{j=1}^{P}\sum_{k=1}^{V}\sum_{t=1}^{T}\Omega_{ijkt} \cdot x_{ijkt}. \tag{3.20}$$

The constraints of the risk minimization model are not affected by changing the objective function.

3.4 Objectives of the Research and Procedure

The objective is to analyze the relationship between the evacuation strategies that are generated by a duration minimization and by a minimization of the overall risk. This includes a better understanding of both strategies and the reaction to various changes in the parameters. The duration minimization model creates evacuation plans that minimize the last arrival of a patient at a receiving hospital while not considering the risk. The risk minimization model minimizes the overall risk of the whole evacuation but creates plans that have a later arrival of the last patient. In addition, the duration minimization model is computationally more intensive than the risk minimization model. It would therefore be ideal to identify parameter changes that can force the properties of the evacuation plans created by the risk minimization model to be closer to those of plans created by the duration minimization model. Since the risks have to be estimated, no variation of the risk parameters describes a real situation exactly. In general, it would be desirable to generate an evacuation plan that is both very fast, close to risk-minimal and computationally not intensive. To this end, different changes in the risk parameters are to be evaluated in terms of the effects on the risk minimization model. In addition, the objective function using probabilistic risks is to be exchanged for an objective function using penalties.

A first step is to change the threat risks to equal risk functions for all patient types. It is expected that there will be no separation of patient types in the evacuation order. This change is not necessarily realistic and serves to analyze the situation further since it could force the risk-minimizing strategies to produce plans that are closer to the plan generated by the duration-minimizing strategy.

In addition, a change to equal transportation risk functions for all patient types has to be considered which should eliminate the separation in the assignments of patient types to special vehicle types. This change is also not realistic and only necessary for a better understanding.

Another modification is to change the travel risk from being constant over time to a risk that increases with time. This could decrease the tendency in the risk-minimizing strategy to fill up the closest hospitals first. It could, however, also have an effect on the distribution of different patient types with time. This modification does not have a realistic background. It could, however, help to approach both strategies.

It is also possible to make the generation of an evacuation plan a two-step-procedure. That is, a duration minimization model is used first to determine the best evacuation time that is possible under the given circumstances. This time is then used as a limit to the risk minimization model to determine how much decrease in the overall risk is possible while still reaching the best evacuation time.

Another change in the risk functions is to decrease the differences in the travel risks between the different vehicle types. Instead of bringing the risk groups closer together, as described earlier, this would bring the risks assigned to the vehicle types closer. The results of this approach might depend on the relation of the number of patients and the number of available vehicles.

Since the threat risks are set arbitrarily and are hypothetical, the last step of this research is to eliminate the probabilistic risks that are currently used in the HETM and in Bish et al. (2014). Instead, the objective function that minimizes penalties which is presented in Section 3.3 is used. This approach has not been used for the HETM before and has the advantage that it does not use hypothetical risk functions. It would also be helpful if this approach was computationally less intensive. The other ideas mentioned for the objective function using probabilistic risks can then be used to determine how those penalties have to be distributed to obtain a good evacuation transportation plan. In order to compare that plan to the basic cases, the overall risk still has to be computed, but other objectives as the duration and the assignment of patients to vehicles are also considered.

For the generation of real evacuation plans, it is important to consider the trade-off between time and risk and to find a solution that does not only consider one objective. This research is intended to determine more insights about the differences between these two opposing strategies and maybe even to determine how these strategies can be forced to converge to one strategy that offers a good evacuation duration as well as a good overall risk of evacuation.

Chapter 4

Results

This chapter describes the results from the ideas outlined in Section 3.4. As a basis, the results for basic scenarios are presented in the first section. After this, the first approaches that use the probabilistic risks and manipulate the risk parameters to change the results of the risk minimization are combined in Section 4.2, the results of replacing the probabilistic risks with penalties is described in Section 4.3.

4.1 Results for Basic Scenarios from the Hospital Evacuation Transportation Model

As mentioned, there are different ways to evaluate the resulting evacuation transportation plans. Some properties can be presented in numbers, others are presented in two different types of diagrams. Figure 4.1 shows how many patients of each type leave the hospital in each time interval and start the loading process into a vehicle. The dark blue bars represent the patients of the most critical patient type 1. The red bars represent the middle critical patient type 2 and the green bars represent the least critical patient type 3.

One example for the second type of diagrams is Figure 4.3. These diagrams show the evacuation from the side of the receiving hospitals. Every marker in these diagrams shows the time interval in which that patient of a patient type left the evacuating hospital who will fill up the beds for the patient type in the receiving hospital over the route time of the hospital. Multiple markers at the same route time can occur as some hospitals have the same route time from the evacuating hospital. The first set of markers shows the time interval of the departure of the last patient of the most critical patient type, the second set of markers represents the middle critical patient type, and the third set of markers the least critical patient type. If there is a marker of the most critical patient type at time interval 20 for a route time of 5, this means that there is a receiving hospital with a route time of 5 time intervals which has beds for the most critical patient type, that the last patient for this bed category leaves the evacuating hospital at time interval 20, and that there will be no more patients of the most critical patient type departing to this hospital. If there is no marker for a given route time, that does not necessarily mean there was no patient transported to a hospital with this route time, it only means that the bed category was not filled up completely.

Following, the results of the HETM with the risk minimization objective function and the duration minimization objective function are presented.

Figure 4.1 shows how patients are assigned to leave the evacuating hospital in a scenario with a constant threat risk in every time interval and no buses available.

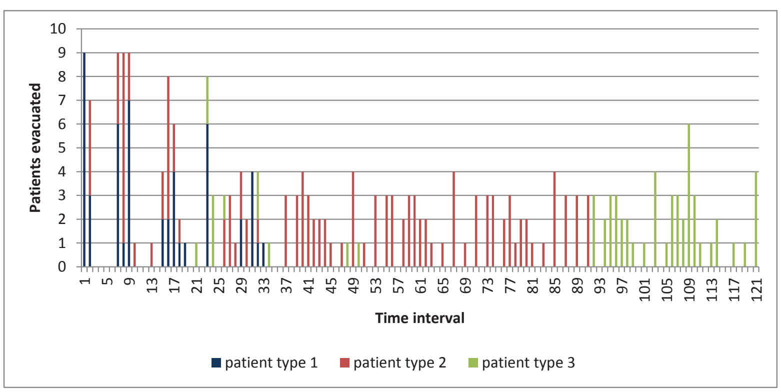

Figure 4.1: Patient evacuation order: risk minimization, basic scenario, constant threat risks, only ambulances

The risk-minimization strategy, with and without buses, tends to transport the most critical patients first. Other patients are also transported during that time, but the last patient of the first and most critical patient type leaves the hospital before the last patient of the second group. The last patient of the second type leaves the hospital before the last patient of the third and least critical patient type. The time distance between the last patients of each risk type differs depending on the threat risk scenario (constant, linear, exponential) and whether or not buses were available but there is a clear overall tendency. Figure 4.2

presents the same situation with buses available starting in time interval 4.

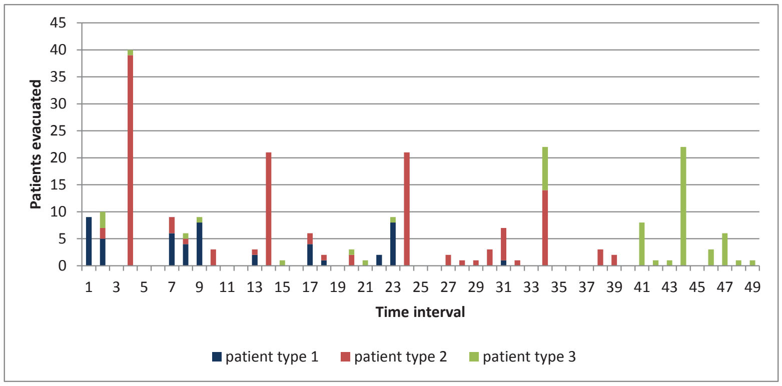

Figure 4.2: Patient evacuation order: risk minimization, basic scenario, constant threat risks, ambulances and buses

In addition to this, a linearly increasing threat risk as well as an exponentially increasing threat risk were tested as they were used in Bish et al. (2014). The different threat scenarios have many effects, the most obvious ones are the overall risks. Table 4.1 shows the different overall risks, the last pickup, and the last delivery for a risk minimization with the given transportation risks and the different threat risk scenarios.

Table 4.1: Duration and risks in different threat scenarios, ambulances and buses

Threat scenario	Interval of last pickup	Interval of last delivery	Overall risk
Constant	49	58	9.0451
Linear	47	54	5.4832
Exponential	51	58	2.0617

Table 4.2 shows how many patients of the patient types are transported in the vehicle types in the different threat risk scenarios. P1 describes the most critical patient type, P3 the least critical patient type. V1 is the best equipped vehicle type, V3 is the bus, which is the worst equipped vehicle type.

Table 4.2: Vehicle assignments in different threat scenarios, ambulances and buses

	P1/V1	P1/V2	P1/V3	P2/V1	P2/V2	P2/V3	P3/V1	P3/V2	P3/V3
Const.	37	13	0	7	29	93	10	24	27
Lin.	40	10	0	6	33	90	10	21	30
Exp.	50	0	0	5	48	76	7	10	44

In a scenario with an exponential threat, the separation of patients to vehicles is stronger than in a constant or linear threat scenario. This means that there are more critical patients transported in the best vehicles in the exponential threat risk scenario than in a constant threat risk scenario.

The other important observation is that there is a tendency of filling the beds in those hospitals first that are closest to the evacuating hospital. Due to the tendency to transport the more critical patients first, the beds for the most critical patient type are often filled first. Figure 4.3 shows the time intervals in which the last transport for a bed category at a hospital in the given distance is started at the evacuating hospital for a constant threat risk without availability of buses.

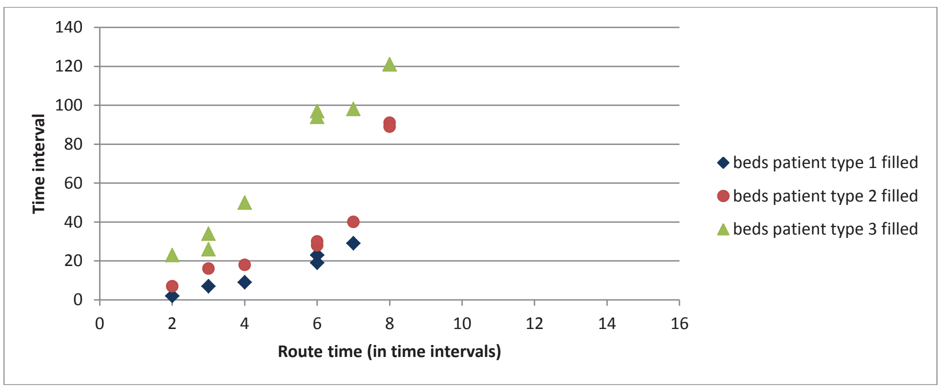

Figure 4.3: Hospital beds: risk minimization, basic scenario, constant threat risks, only ambulances

It can be noticed that, as the more critical patients leave the evacuating hospital earlier, those beds are also filled earlier. However, the relation between the route time and the time interval of the last patient behaves almost linearly for the two smaller patient categories, the most and least critical one, whereas the relation for the second patient type appears to be almost exponential. It can also be seen that there are hospitals that are further away whose hospital beds are not filled up as there are more beds available in the receiving hospitals than patients in the evacuating hospital.

This tendency of filling the beds for the most critical patients first is, however, not always strictly kept and some categories of hospital beds are not filled up completely. This is especially true for the scenarios with buses where it can be advantageous to transport patients to a hospital that has a longer route time but more available beds than a closer hospital because it is then possible to send a bus. Figure 4.4 shows this for a scenario with buses available.

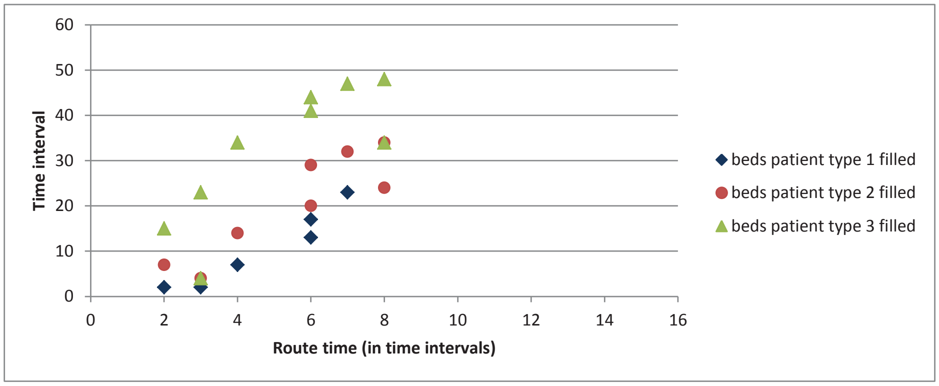

Figure 4.4: Hospital beds: risk minimization, basic scenario, constant threat risks, ambulances and buses

Here, the separation is not as clear as in Figure 4.3 and there are also more outliers to any tendency than in the scenario without buses.

The following thesis will focus on the threat risk scenario that assumes a constant threat risk as the overall tendencies are comparable although not identical. The risk scenarios and the values are not determined analytically and Table 4.1 also shows that the overall risk can be higher for a constant threat risk which seems unintuitive but is due to the fact that the large increase in the cumulative threat risks occurs later for a linearly or exponentially increasing threat risk.

With a duration minimization without rules for the assignment of patients to vehicles, the situation is considerably different than in a risk minimization scenario. Figure 4.5 shows in which order patients of different patient types are chosen to leave the evacuating hospital when buses are available.

The last patients of the three patient types leave the hospital in the same or close time intervals, both with and without availability of buses. Throughout the whole evacuation process, patients of all risk groups are mixed. This result was expected as the duration minimization does not consider the differences between the patient characteristics. The same result therefore also holds true if no buses are available.

Furthermore, the closest hospitals are not filled very early if no buses are available. How beds are filled up in the receiving hospitals with a duration minimization without buses is shown in Figure 4.6.

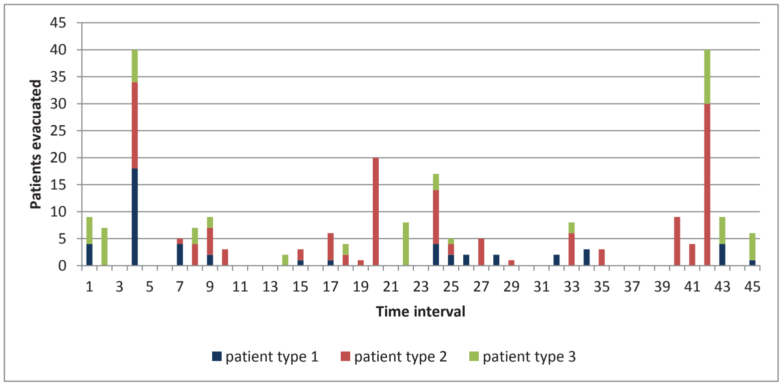

Figure 4.5: Patient evacuation order: duration minimization, basic scenario, ambulances and buses

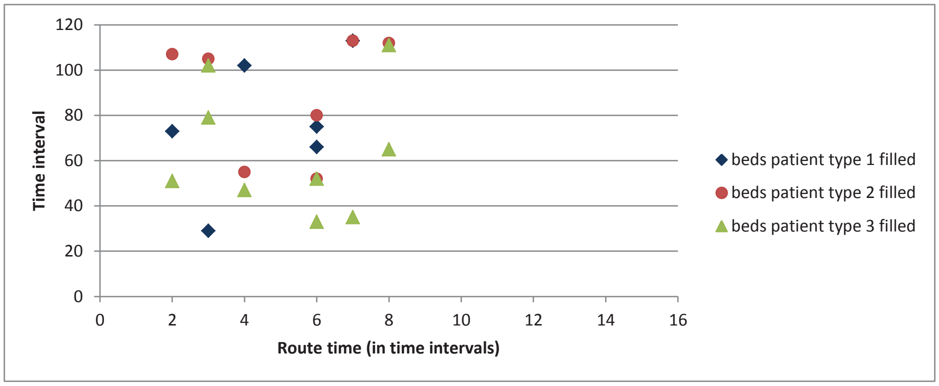

Figure 4.6: Hospital beds: duration minimization, basic scenario, ambulances

It can be seen that there are last patients being transported to both very close hospitals as well as to more distant hospitals. In addition to this, the beds for the least critical patient type are filled up first in some hospitals when no buses are available. This lack of separation of patient types was explained earlier.

The first of two possible sets of rules for the assignments of patients to vehicle types for the duration minimization is the most restrictive and allows only one vehicle type for every patient type. The second set of rule also allows for an upgrade in those assignments. If the two sets of rules for the assignment of the patients to the different vehicles are used, the duration of the evacuation transportation increases significantly. Due to this increase in duration, the overall risk also increases because the potential decrease in transportation risks cannot balance the increase in the threat risk in the hospital the patients have to face. Table 4.3 shows the durations and overall risks for the three different rule sets for the assignments in a scenario with buses for a constant threat risk in the hospital.

Table 4.3: Rule sets in duration minimization with ambulances and buses and a constant threat risk

Rule set	Interval of last pickup	Interval of last delivery	Overall risk
Unrestricted	45	52	12.601
Upgrades possible	81	89	17.933
Hard restrictions	127	136	26.351

It is therefore not interesting to discuss other variations than the unrestricted duration minimization other than for the fact that the assignment of patients to vehicles is an issue that has to be considered when finding a good evacuation transportation plan.

In summary, there are some substantial differences between evacuation plans created with a risk-minimizing and a duration-minimizing strategy. The evacuation transportation plans generated with the risk minimization model tend to have longer durations and a more clear separation of the assignments of patients to the vehicle types while the plans created by the duration minimization do not consider the specific characteristics of the different patient types. The assignment of patients to vehicles can be manipulated in the duration-minimizing approach by changing the rules. With the most flexible rule set that was used for these first insights the two different strategies differ mostly in the way the patients are sorted in terms of the time interval to leave the hospital and in the way the hospital beds are filled. The specific evacuation plans differ though, this is depending on the problem size and especially on the proportion of patient group sizes as well as on the proportion of patients and vehicles. The duration minimization, however, requires more computational effort and provides a plan with an earlier last delivery in comparison to the risk minimization which provides plans with smaller overall risks.

4.2 Parameter Changes in Probabilistic Risk Functions

The following section focuses on different aspects how the risk parameters can be adjusted to force the risk minimization model to find different evacuation transportation plans. The overall risk values are still computed with the basic values so that the changed plans can be evaluated in terms of the overall risks among other measures. In Bish et al. (2014), three different threat scenarios were described and tested. All of those were also used for the subsequent parameter changes, but the focus is on the scenario where the probabilities for negative events are constant for every time interval. Furthermore, both the scenario with only two ambulance types as well as the scenario with additional buses are tested. This means that the basic cases for comparisons are the duration minimization without restrictions with and without buses as well as the risk minimization with a constant threat risk scenario with and without buses.

4.2.1 Equal Threat Risk for all Patient Types

The threat risk parameters for the optimization in these tests were manipulated to be the same for every patient category. The transportation risks were not changed. For the computation of the overall risks for the comparison with the basic risk minimization, the risk parameters that threaten every patient category in a different way were used. This means that two different sets of parameters are used for the generation of the evacuation transportation plan on the one hand and the evaluation of this plan on the other hand. It was also tested whether it makes a difference to assume the threat risk level of the most critical patient type, the middle critical patient type, or the least critical patient type.

The first important results for the problem instance are presented in Table 4.4. Both the overall risk and the two measures for the duration of the evacuation are shown for the duration minimization without restrictions, risk minimization with constant threat risks that affect patient types in different ways and for the risk minimization where all patients have the constant threat risk of the most critical patient type.

Table 4.4: Duration and risks: equal constant threat risk (patient type 1), ambulances only

	Interval of last pickup	Interval of last delivery	Overall risk
Risk, basic	121	130	19.753
Risk, equal threat	118	127	21.655
Duration	113	121	24.187

A similar tendency also holds true for the same scenario with buses available for the evacuation transportation. The durations of the evacuation plans generated with equal threat risks for all patient types both with and without the use of buses are between the durations of the plans generated with the basic risk minimization and the duration minimization. The only exception occurs when the threat risk function of the least critical patient type was used. Furthermore, the risks resulting from the manipulated threat risks are lower than the ones generated by a duration minimization and higher than the ones in a risk minimization with original threat risks which can be seen in Table 4.4. The results are only slightly different if all patients face the threat risks of the middle or least critical patient type, those outcomes are therefore not included in the table.

The results are probably due to the fact that the separation of patient types in the order of transportation is changed into another separation which is shown in Figure 4.7 for a scenario without buses.

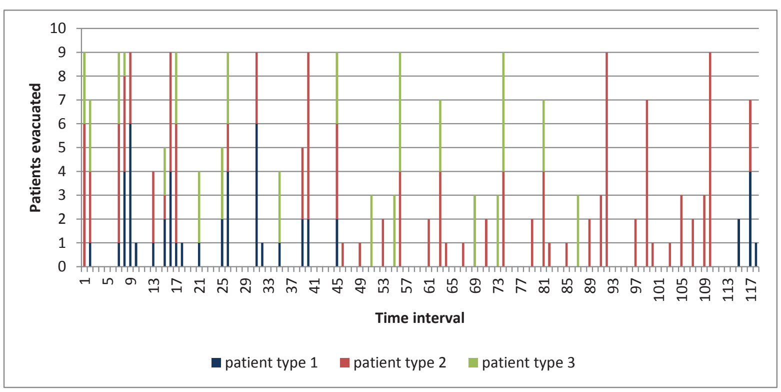

Figure 4.7: Patient evacuation order: risk minimization, equal constant threat risks (patient type 1), ambulances only

Without the use of buses, patients of all types are transported in the first time intervals until almost all patients of the most critical type are transported, but the last patients of that patient type have to wait until almost the end of the evacuation transportation process. The patients of the least critical type complete the evacuation transportation first. Figure 4.8 presents the situation with buses.

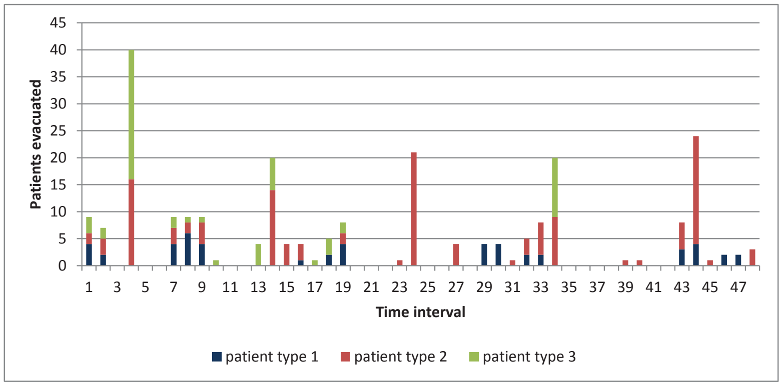

Figure 4.8: Patient evacuation order: risk minimization, equal constant threat risks (patient type 1), ambulances and buses

The new separation might be induced by the fact that the travel risk is the only factor that distinguishes the patient types. Due to this, the assignments of different patient types to the vehicle groups are separated stronger than in the basic scenario with a constant threat risk scenario and can be seen in Table 4.5.

Table 4.5: Vehicle assignments: equal constant threat risk without and with buses

	P1/V1	P1/V2	P1/V3	P2/V1	P2/V2	P2/V3	P3/V1	P3/V2	P3/V3
Amb.	50	0	-	70	59	-	0	61	-
Bus	50	0	0	12	38	79	0	20	41

It is noticeable that the most critical patients are only transported in the ambulances that cause the smallest travel risk and that instead no patients of the least critical patient type are transported in the best vehicle category.

The differences in the order of patients leaving the hospital can also be seen in how the beds in the receiving hospitals are filled. With the basic duration minimization, beds are filled independently from their proximity to the evacuating hospital and independently from how critical the patient type is. In the basic risk minimization, there is a tendency to fill the beds of the most critical patients first which is related to the order of patients leaving the hospital. The filling up of beds for the scenario where all patients share the threat risks of the most critical patient type can be seen in Figure 4.9.

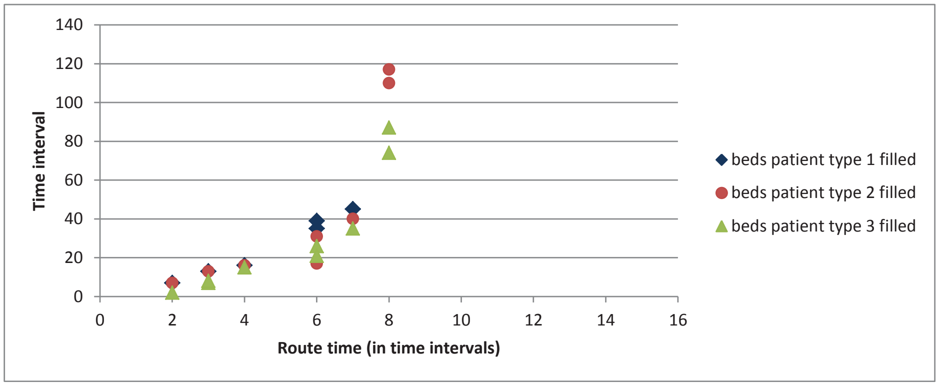

Figure 4.9: Hospital beds: risk minimization, equal constant threat risks (patient type 1), ambulances only

When the risk minimization is run with threat risks that are equal for all patients, there is almost no difference in the patient categories but the relationship between time interval and route time is approximately exponential for scenarios without buses. When buses are available, the situation is more complicated, the relationship cannot be described that easily and is therefore shown in Figure 4.10.

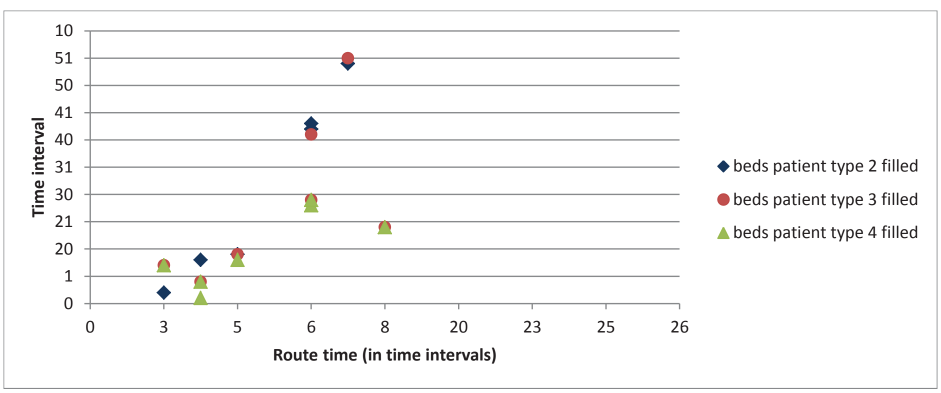

Figure 4.10: Hospital beds: risk minimization, equal constant threat risks (patient type 1), ambulances and buses

There is, however, still a relation between the distance of the receiving hospitals and the time interval in which the last patient of a patient type leaves the evacuating hospital for a specific bed category. This means that the closest hospitals are filled up very early to make the vehicles available for the rest of the evacuation process.

In summary, this manipulation of the optimization parameters leads to evacuation plans that show properties between the risk minimization with the original parameters and a duration minimization in terms of the overall risk and the duration. Also, the beds in the closest hospitals are filled first. This strategy might not be applicable if it is desired to evacuate patients of a certain patient type first.

4.2.2 Equal Transportation Risk for all Patient Types

In this subsection, the transportation is assumed to affect every patient in the same way which means that the travel risks for the optimization are equal for every patient. The threat risks are assumed to be different for the different patient types. For a comparison with the basic minimization strategies, the real overall risk is computed with different travel risks for the patient types.

Assuming that all patients experience those travel risks of the most critical patient type, the most interesting difference to notice concerns the duration and the overall risk and is presented in Table 4.6 for a scenario without buses and in Table 4.7 for the same scenario with buses, both in comparison with the basic results from risk minimization and duration minimization.

Table 4.6: Duration and risks: equal transportation risk (patient type 1), ambulances only

	Interval of last pickup	Interval of last delivery	Overall risk
Risk, basic	121	130	19.753
Risk, equal travel risk	119	128	19.8737
Duration	113	121	24.187

If the evacuation transportation process is run with only two types of ambulances, the duration is between the two basic scenarios, but both the durations as well as the overall risk are closer to the risk minimization with differences in travel risks. If all patients face the travel risks of the middle or least critical patient category, the evacuation takes slightly less time, the last departure is in time interval 117, the last delivery in time interval 126, and the overall risks are very close to the scenario in which all patients face the travel risks of the most critical patient type.

The durations of this modification are longer than both the duration and the basic risk

Table 4.7: Duration and risks: equal transportation risk (patient types 1,2 and 3), ambulances and buses

	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	49	58	9.0451
Risk, equal travel risk (P1)	85	94	13.346
Risk, equal travel risk (P2)	50	59	10.9408
Risk, equal travel risk (P3)	50	59	10.8930
Duration	45	52	12.601

minimization if buses are available and all patients experience the travel risks of the most critical patient type. This results also in higher overall risks as many patients have to stay in the evacuating hospital. Even if all patients face the smaller travel risks of the second or third patient type, the evacuations take slightly longer than in evacuations planned with the basic risk minimization.

Another interesting observation is that far less buses are used if all patients experience the travel risk of the most critical patient type than in plans generated by the basic risk minimization or the duration minimization. If the travel risks are smaller, however, many buses are used to transport patients of all patient types. This also explains why the duration is long for a high travel risk. The assignments of patients to vehicles for the scenario that assumes the same travel risks of the most critical patient type for all patient types are shown in Table 4.8.

Table 4.8: Vehicle assignments: constant equal travel risk (patient type 1) without and with buses

	P1/V1	P1/V2	P1/V3	P2/V1	P2/V2	P2/V3	P3/V1	P3/V2	P3/V3
Amb.	22	28	-	68	61	-	35	26	-
Bus	8	17	25	51	43	35	40	21	0

The most interesting fact is that the overall number of patients transported in vehicles of type 3 (buses) is smaller than in the basic risk minimization. Apart from that, it can be noticed that there is no further separation of patient types in the vehicle assignments.

The overall risks are also higher than the overall risk in the risk minimization without manipulations, but smaller than in the duration minimization. The reason for this lies in how patients are chosen to leave the evacuating hospital. The clear separation of patient types that can be seen for the scenario of the highest travel risks without buses in Figure 4.11 was expected as the threat risk in the hospital is the only parameter here to distinguish patients.

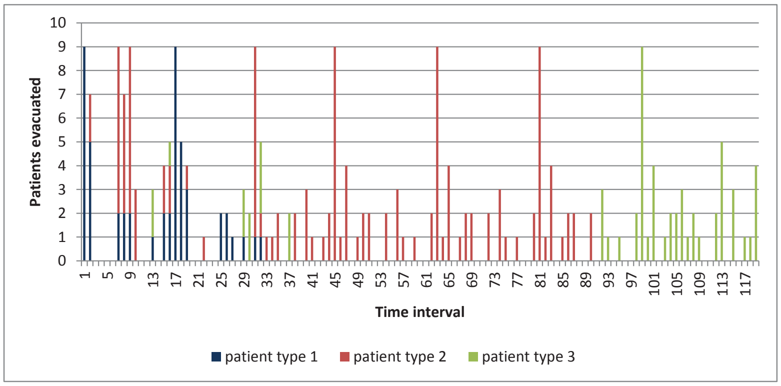

Figure 4.11: Patient evacuation order: risk minimization, equal travel risks (patient type 1), ambulances only

The most critical patients are transported first, most of the least critical patients have to wait longer. The separation of patient categories also has an effect on the hospital beds. While the beds in the closest hospitals are filled first, the beds for the most critical patients are also filled up first within the hospitals. The leaving time of the patient of a specific category that fills up a bed category is depicted in Figure 4.12 over the route time of the receiving hospitals and for a scenario without buses.

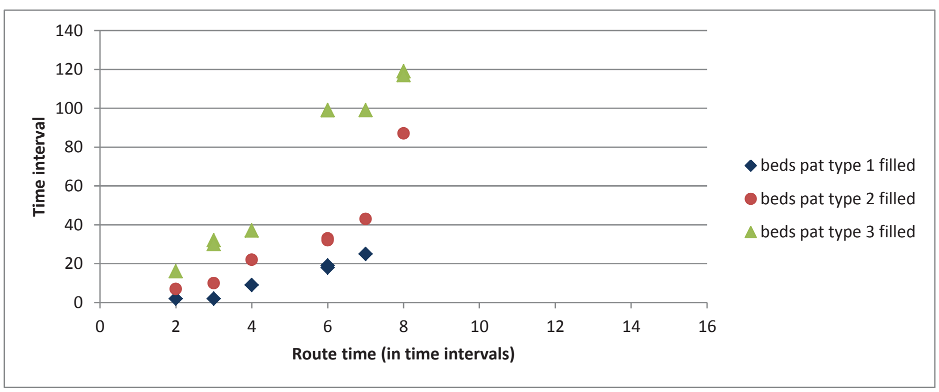

Figure 4.12: Hospital beds: risk minimization, equal travel risks (patient type 1), ambulances only

The conclusion about this manipulation is that an even stronger separation of patients in the order of leaving the evacuating hospital can be enforced by assuming for the optimization that all patients face the same risks when traveling with certain types of vehicles. This can lead to higher overall risks due to longer evacuations. Instead, the separation of certain patient types to vehicle types is eliminated which is against the objective to transport patients in vehicles that are best for their situation.

4.2.3 Limiting the Risk Minimization with a Duration

This subsection follows a strategy in which the parameters are not changed. Instead, the duration of the duration minimization strategy is used as an upper bound on the risk minimization. Since there is no strategy with a shorter duration, this also means that the risk minimization now has an enforced duration. As mentioned in Section 3.4, this cannot be an idea to be pursued in the future as this is computationally more extensive than both strategies alone.

The duration minimization minimizes the duration until the last patient reaches a receiving hospital. Another important measure, however, is the duration until the last patient leaves the evacuating hospital. Since the routing time to the receiving hospitals is constant, the risk minimization itself does not consider the last time interval a patient reaches a hospital.

The durations and overall risk values for the two basic cases as well as the restricted risk minimization for both a scenario with and without buses are presented in Table 4.9.

Table 4.9: Duration and risks: restricted risk minimization, ambulances only and ambulances with buses

Ambulances	Interval of last pickup	Interval of last delivery	Overall risk
Risk, basic	121	130	19.753
Risk, restricted	113	121	19.91
Duration	113	121	24.187
Bus	**Interval of last pickup**	**Interval of last delivery**	**Overall risk**
Risk, basic	49	58	9.0451
Risk, restricted	45	52	10.13
Duration	45	52	12.601

Both sorts of durations were equal to the ones from the duration minimization. In addition, the overall risk was considerably closer to the original risk minimization than to the duration minimization.

The main reasons for this difference in the overall risk are on the one hand the assignments of patient types to vehicle types that are not considered in the duration minimization, and the order of how patients leave the evacuating hospital on the other hand which can be seen in Figure 4.13 for the scenario with ambulances and buses available for the evacuation transportation.

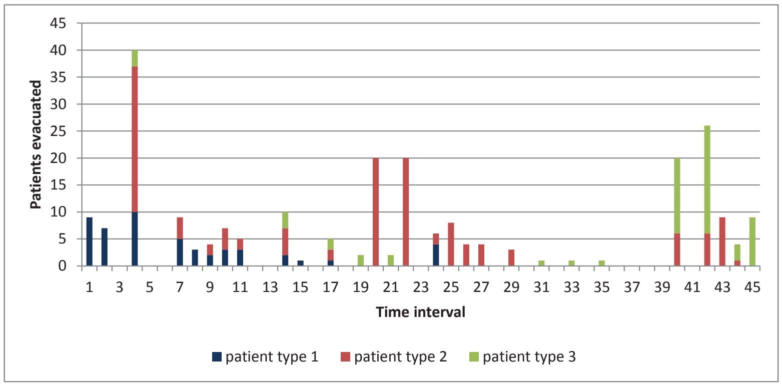

Figure 4.13: Patient evacuation order: risk minimization, restricted, ambulances and buses

Most of the most critical patients are transported early while the less critical patients wait longer in the evacuating hospital.

In contrast to the evacuation transportation plan generated with the duration minimization model, the restricted risk minimization also fills those beds in the closest hospitals first. This is especially true for a scenario without buses, but the same tendency also holds true when buses are available as can be seen in Figure 4.14.

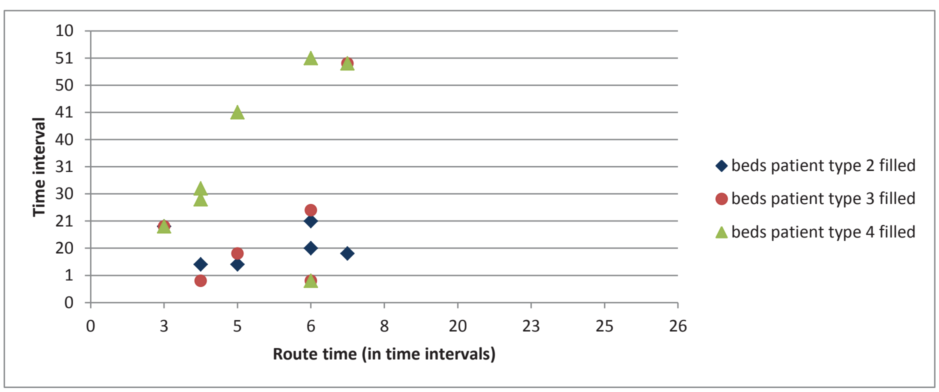

Figure 4.14: Hospital beds: risk minimization, restricted, ambulances and buses

In general, this solution would be a good compromise as this restricted risk minimization seems to improve the solution of the duration minimization by changing patient orders and vehicle assignments. This does, however, mean that both models have to be used which is not practicable in the case of an emergency. The other downside is that for some reasons, that cannot be found within the scope of this thesis, the restricted risk minimization could not be run for this problem instance with an exponential threat risk and buses before running out of memory.

This experiment did show that it is possible to find evacuation plans with the shortest durations possible while getting closer to the minimal risk that can be achieved. This insight is very valuable and also presents more information about the trade-off between duration and risk. Figure 4.14 also shows that the approaches in Subsections 4.2.1 and 4.2.2 are more tending towards extremes like clear separations of patients than the solution obtained here and that it might therefore be difficult to obtain an evacuation transportation plan with risk values and durations as good as obtained in this subsection.

4.2.4 Increasing Transportation Risk

Throughout the last sections and subsections as well as in Bish et al. (2014), the transportation risk was computed as

$$\Theta_{ijk} = 1 - (1 - \beta_{jk})^{(\tau_i + 2\gamma_k)}, \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V \tag{4.1}$$

using β_{jk} which describes the travel risk for a patient of type j in a vehicle of type k. Since the travel risk is constant, the transportation risk did not depend on the time interval t in which the evacuation transportation process for the patient started.

In order to evaluate how the transportation risk influences the risk minimization, the computation of the transportation risk was changed for this subsection to a formulation where the transportation risk of a certain patient in a certain vehicle is smaller if it happens earlier. The transportation risk is therefore computed as

$$\Theta_{ijkt} = 1 - (1 - \frac{t}{T} \cdot \beta_{jk})^{(\tau_i + 2\gamma_k)}, \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V, t = 1, ..., T. \tag{4.2}$$

In order to compare the evacuation plans, the overall risks of the generated plans were still computed with travel risks that do not increase with time.

T is the maximum time allowed for the evacuation of all patients and is set higher than the actual evacuation durations and here set to 150 time intervals. Since the generated evacuation transportation plans do not reach this limit, especially if buses are available during the evacuation transportation, the transportation risks that are used for the actual optimization are smaller than the ones that were used for the optimization with the original risks. Due to this, another set of runs was performed where the transportation risk was computed as

$$\Theta_{ijkt} = 1 - (1 - 2 \cdot \frac{t}{T} \cdot \beta_{jk})^{(\tau_i + 2\gamma_k)}, \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V, t = 1, ..., T \quad (4.3)$$

to have a situation with transportation risks that are closer to the level of the original risk.

The effects of the two changes in the computation of the transportation risk on the two durations and the overall risk are presented in Table 4.10. The threat risks for all presented cases are constant in every time interval.

Table 4.10: Duration and risks: risk minimization, increasing travel risks, ambulances only and ambulances with buses

Ambulances	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	121	130	19.753
Increasing travel risks (t/T)	117	126	19.806
Increasing travel risks (2t/T)	117	126	19.785
Duration	113	121	24.187
Bus	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	49	58	9.0451
Increasing travel risks (t/T)	49	56	9.9711
Increasing travel risks (2t/T)	49	56	9.9703
Duration	45	52	12.601

It is noticeable that the durations for both variations are the same and the overall risks are only slightly apart. Both variations obtained results that are closer to the basic risk minimization than to the duration minimization when buses are available. When the evacuation transportation is organized without buses, however, the overall risks of the two new strategies are close to those of the risk minimization while achieving durations that are almost in the middle of the basic risk minimization and the duration minimization strategy.

Another interesting result with this modification is the assignment of patient types to vehicle categories. Table 4.11 summarizes those assignments for constant threat risks and both a scenario without and a scenario with buses.

Table 4.11: Vehicle assignments: increasing travel risks without and with buses

t/T	P1/V1	P1/V2	P1/V3	P2/V1	P2/V2	P2/V3	P3/V1	P3/V2	P3/V3
Amb.	30	20	-	60	69	-	30	31	-
Bus	22	13	15	18	26	85	15	26	20
2t/T	P1/V1	P1/V2	P1/V3	P2/V1	P2/V2	P2/V3	P3/V1	P3/V2	P3/V3
Amb.	34	16	-	56	73	-	26	35	-
Bus	22	13	15	18	26	85	15	26	20

It is interesting to notice that there is not a very strong separation of risk types in the assignments of patients to the vehicle groups and that the assignments are made in the same way for both scenarios of increase in the travel risk if buses are available.

In the basic risk minimization with a constant threat risk, 5 buses are used that are all completely filled and depart to the hospitals 1, 8, and 10. In the duration minimization strategy, 6 buses are used that transport patients to the hospitals 1, 2, 10, 11, and 12 although one bus transports only 17 out of 20 patients. It can be noticed that the route times are 3 time intervals for hospital 8, 6 time intervals for hospital 11, 7 time intervals for hospital 2, and 8 time intervals for hospitals 1, 10, and 12. In the two scenarios with increasing travel risk, 6 buses are used that are all completely filled and transport patients to the hospitals 8, 10, and 11.

The Figures 4.15 and 4.16 show in which order patients are leaving the evacuating hospital. Both are assuming a constant threat and no available buses, Figure 4.15 depicts the scenario with a factor of $\frac{t}{T}$, Figure 4.16 with the other factor $2\frac{t}{T}$.

One observation is that there are more outstanding peaks in the number of patients of one risk category transported in one time interval. In addition, there are recurring patterns in the middle of the evacuation transportation that are more obvious than in the basic risk minimization with a constant travel risk. Apart from that, the patient orders are similar in that the patients of the most critical patient type are evacuated earlier, while less critical patients have to stay in the hospital longer, but the time intervals of those last patients leaving are close to the basic scenario. If buses are available, the most critical patients are evacuated even faster. While the last patient of this patient type leaves the hospital in time interval 31 in the basic risk minimization, the risk minimizations with increasing travel risk obtain evacuation plans where the last patient of the most critical type leaves in time interval

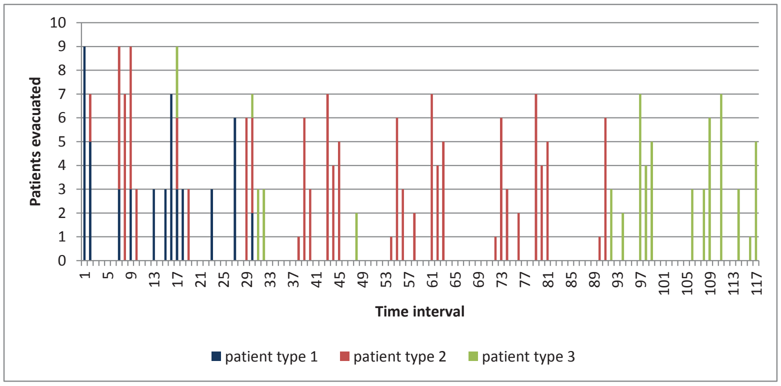

Figure 4.15: Patient evacuation order: risk minimization, increasing travel risk with factor $\frac{t}{T}$, ambulances only

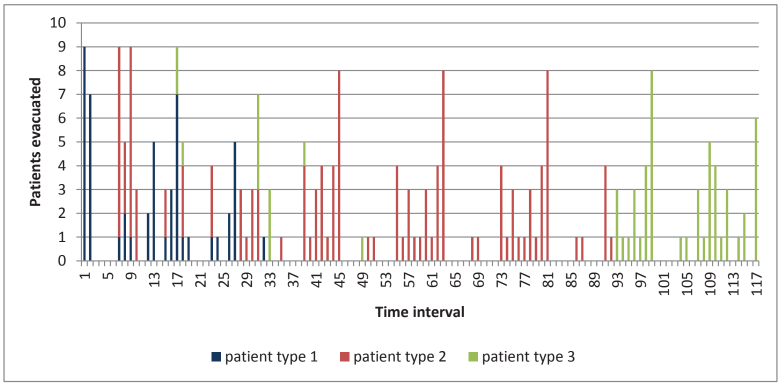

Figure 4.16: Patient evacuation order: risk minimization, increasing travel risk with factor $2\frac{t}{T}$, ambulances only

13.

Since the main characteristics as duration and last departure time intervals of the different patient types are similar if no buses are available, the filling up of hospital beds looks similar to the scenario with a constant travel risk. With buses, the diagrams look similar to each other, Figure 4.17 shows the time intervals in which a patient of a patient type is departing for the last bed of that category over the route time of the hospital for the factor $\frac{t}{T}$, ambulances and buses and a constant threat risk scenario.

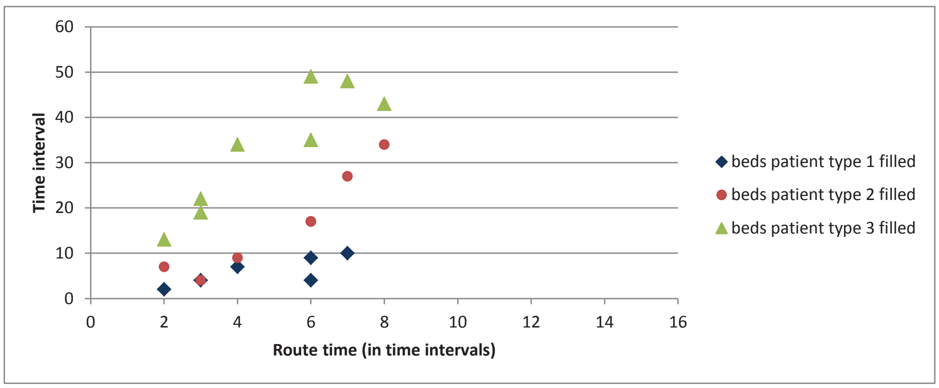

Figure 4.17: Hospital beds: risk minimization, increasing travel risk with factor $\frac{t}{T}$, ambulances and buses

The diagram for the factor $2\frac{t}{T}$ has more outliers in the furthest hospitals that are receiving patients but is very similar to Figure 4.17 apart from that. Both show more outliers and less of a linear structure than the one for the basic risk minimization (Figure 4.4).

In summary, it is interesting that without the use of buses, the changes of the travel risk can lead to evacuation transportation strategies that are faster than the basic risk minimization while having overall risks that are still close to the best possible risk and while also filling the closest hospital beds first. If buses are available and the evacuation transportation durations are shorter than without buses, the evacuations are not faster than the basic risk minimization but have higher overall risks.

4.2.5 Decreasing the Differences between Travel Risks of Different Vehicle Types

The travel risk is the parameter that describes the risk of transportation for a patient of a given patient type for one time interval of travel in a certain vehicle type. The following Table 4.12 provides the travel risks that were used for the basic risks and the first set of new travel risks.

Table 4.12: Basic and new travel risks for patient types and vehicle types

basic	ALS (vehicle type 1)	BLS (vehicle type 2)	Bus (vehicle type 3)
Patient type 1	0.001	0.002	0.01
Patient type 2	0.0001	0.0002	0.0005
Patient type 3	0.00005	0.00005	0.0001
new	ALS (vehicle type 1)	BLS (vehicle type 2)	Bus (vehicle type 3)
Patient type 1	0.001	0.0015	0.002
Patient type 2	0.0001	0.00015	0.0002
Patient type 3	0.00005	0.00005	0.00007

The results in this subsection can be summarized more briefly as even these changes in the risk functions did not improve the durations considerably. The two measures for the duration, the last departure, and the last arrival are presented in Table 4.13 for the basic risk minimization, the risk minimization with the new travel risk parameters, and the duration minimization.

Table 4.13: Duration and risks: closer travel risks, ambulances only (a) and ambulances and buses (b)

(a)	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	121	130	19.753
Risk, closer travel risks	120	129	19.7617
Duration	113	121	24.187
(b)	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	49	58	9.0451
Risk, closer travel risks	49	58	9.7668
Duration	45	52	12.601

These results are not very promising as there is no improvement in the durations if buses are available and only a small decrease in the durations if the evacuation process is planned

without buses. Since the overall risks cannot be smaller than those achieved with the basic risk minimization, this approach is not promising. Some reasons for the achieved results might be that vehicles are the limiting factor in this problem instance and that the differences between the travel risks of the different patient types was not changed as it was done in Subsection 4.2.2. If there is only one vehicle, the differences between the risk characteristics of the patients are considered in this scenario. This concept might, however, lead to better results if there were more vehicles in relation as the situation of patients having to choose between multiple vehicles might occur more often then.
Completely giving up the separation of travel risks for the different vehicle types is not promising in terms of the result as it is an objective of the evacuation transportation planning to transport patients in those vehicles that are equipped best for their needs. If the separation was eliminated, patients would have the same travel risks for all vehicle types. There would be only one reason left to transport patients in an ambulance rather than in a bus which is that the loading time, which also counts into the transportation risk, is higher for a bus than for an ambulance.

4.3 Penalty Approach

In this section, the probabilistic risks are to be exchanged for a penalty approach that adds penalties for patients staying in the evacuating hospital or for assigning patients of a certain risk group to a certain vehicle type. The insights from Section 4.2 can be used to define the penalties.

As this objective function behaves considerably different than the objective function using probabilistic risks, the factors φ_{jk} and μ_j cannot be derived easily from the probabilistic risk functions. This is mostly due to the fact that the probabilistic risks do not behave linearly as can be seen in Figure 3.1. The factors φ_{jk} and μ_j have to be determined such that the evacuation plans generated with this objective function have desirable properties.

The following first subsection presents two sets of factors φ_{jk} and μ_j such that the resulting evacuation transportation plans come close to those resulting from a basic risk minimization strategy. The second subsection presents sets of factors that were modified based on the insights created in Section 4.2. The third subsection then gives an overview about computational efforts, and the last subsection summarizes the insights from the developed penalty approach.

4.3.1 Basic Set of Penalty Factors

This subsection presents two sets of factors for the penalty approach whose resulting evacuation transportation plans show desirable properties in terms of the overall risk and do not result in durations longer than those from the basic risk minimization.

The two sets of factors are presented in Table 4.14. It is obvious that the factors are chosen in a way that is adapted from the risk functions in the risk minimization approach as a minimal or close to minimal overall risk is a desirable property.

Table 4.14: Basic sets of factors for penalty approach

Set 1	φ_{j1}	φ_{j2}	φ_{j3}	μ_j
Risk group 1 (j=1)	8	16	35	24
Risk group 2 (j=2)	2	3	4	18
Risk group 3 (j=3)	1	1	2	12
Set 2	φ_{j1}	φ_{j2}	φ_{j3}	μ_j
Risk group 1 (j=1)	8	16	35	25
Risk group 2 (j=2)	2	3	4	20
Risk group 3 (j=3)	1	1	2	15

The following Table 4.15 presents the overall risks assuming a constant threat risk in each time interval as well as the two sorts of durations for the basic scenario in the risk minimization, for the duration minimization, and the two sets of factors φ_{jk} and μ_j for both a scenario with and without the use of buses.

It can be noticed that the penalty approach with these two specific sets of penalty factors generates evacuation transportation plans that have durations that are slightly shorter than those of evacuation plans generated by the risk minimization while having only slightly higher overall risks. The evacuation transportation plans generated with the penalty approach also show some similarity to those generated by the risk minimization in terms of the vehicle assignments and the way how patients are chosen to leave the evacuating hospital. The assignments of patients of the different types to vehicle types is presented for both sets of basic factors in Table 4.16 for a scenario with two types of ambulances and for a scenario with two types of ambulances and buses.

Table 4.15: Duration and risks: basic penalty factors, ambulances only (a) and ambulances and buses (b)

(a)	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	121	130	19.753
Factor set 1	119	128	19.7564
Factor set 2	118	127	19.7858
Duration	113	121	24.187
(b)	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	49	58	9.0451
Factor set 1	49	56	9.0539
Factor set 2	47	56	9.0628
Duration	45	52	12.601

Table 4.16: Vehicle assignments: basic penalty approach without and with buses

Set 1	P1/V1	P1/V2	P1/V3	P2/V1	P2/V2	P2/V3	P3/V1	P3/V2	P3/V3
Amb.	45	5	-	47	82	-	21	40	-
Bus	36	14	0	7	25	97	13	25	23
Set 2	P1/V1	P1/V2	P1/V3	P2/V1	P2/V2	P2/V3	P3/V1	P3/V2	P3/V3
Amb.	49	1	-	43	86	-	22	39	-
Bus	39	11	0	8	28	93	9	25	27

The penalty approach with the two basic sets of penalty factors generates evacuation plans that take the risk characterizations of the patients in terms of the transportation into consideration and assigns most of the most critical patients to the best equipped vehicles, while the majority of the middle and least critical patients are assigned to the second and third vehicle type. This is a desirable property as it concerns the safety of the patients during the transportation.

In addition to the assignments of patients to vehicles, the patients of the various types also leave the evacuating hospital similarly to the plan generated by a basic risk minimization, that is, the last patient of the most critical type leaves the hospital before the last patient of the middle critical type and the last patient of the least critical patient type is the last patient to leave the hospital. This is true for both sets of factors and for both a scenario with only ambulances and a scenario with ambulances and buses. Figure 4.18 shows this for the first set of penalty factors for a scenario without buses.

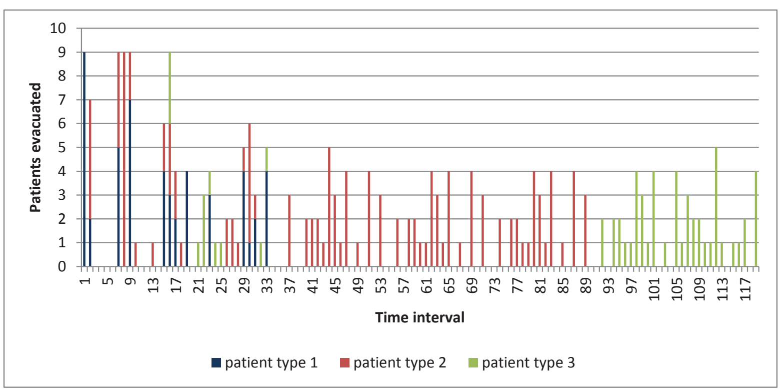

Figure 4.18: Patient evacuation order: penalty approach, set 1 of basic penalty factors, ambulances only

Another aspect relates to how the beds in the receiving facilities are filled with evacuated patients. According to the tendency to evacuate the most critical patients early in the process, the beds for this patient type are filled earlier than other beds. Also, beds in closer hospitals are filled earlier than beds in hospitals with a longer route time. If buses are available, those tendencies are not as strong as it can be more reasonable to send more less critical patients with a bus or an ambulance that is not of the best equipped type and therefore leaving more critical patients in the evacuating hospital to wait for a better equipped vehicle. The tendencies are consistent with the tendencies in the basic risk minimization. Figure 4.19 presents the filling up of bed categories for the second set of basic penalty factors with the availability of buses as an example.

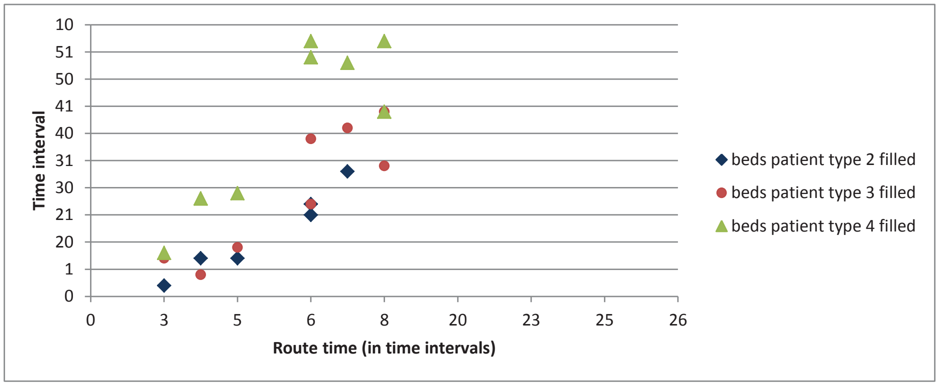

Figure 4.19: Hospital beds: penalty approach, set 2 of basic penalty factors, ambulances and buses

It can be noticed that the filling up of beds for the patients of certain hospitals with route times of 6 and 8 time intervals happen in the same time interval. Those patients are also the last ones to leave the evacuating hospitals. The last arrival is therefore determined by the longer route time. Figure 4.20 shows how beds are filled up for the first set of basic penalty factors when buses are available.

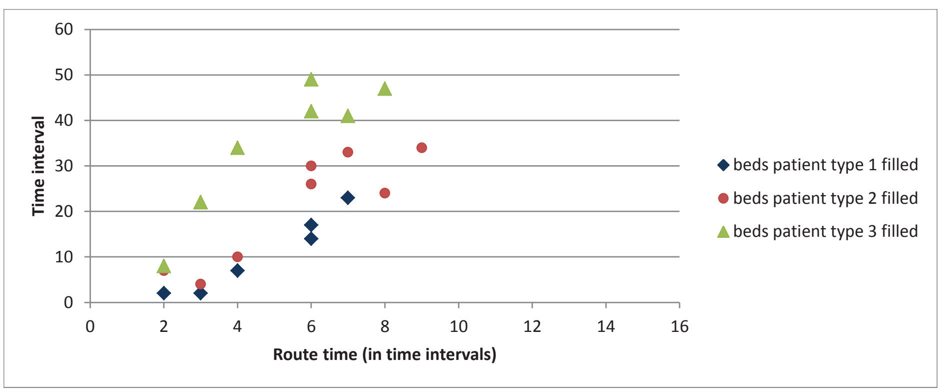

Figure 4.20: Hospital beds: penalty approach, set 1 of basic penalty factors, ambulances and buses

Here, the last patient leaves to a hospital which has a route time of 6 time intervals and arrives there in the same time interval as a patient that departed 2 time intervals earlier to a hospital with route time 8.

In summary, it is possible to generate evacuation transportation plans that have properties very similar to those obtained with the risk minimization approach. Most of the most critical patients are transported with the best equipped ambulances and those patients are also evacuated early in the evacuation process. The durations obtained in evacuation transportation plans generated with these sets of factors in the penalty approach are at least as short as those in risk-minimizing evacuation plans with overall risks only slightly larger.

4.3.2 Modified Penalty Factors

In this subsection, two modifications are tested based upon the insights gained from Section 4.2: giving every patient the same penalties for the stay in the evacuating hospital and increasing the penalties for transportation over time. The main purpose of this is to determine whether the modifications that are able to manipulate the resulting evacuation transportation plans for the risk minimization are also able to manipulate the generated plans in the penalty approach.

The first modification of the penalty factors presented is to change the factors μ_j such that they are equal for every patient type. This means that the critical patients are not evacuated earlier than other patients but this increases the flexibility. For both sets of factors presented in Subsection 4.3.1, the same approach as in Subsection 4.2.1 was used which is to use the factors μ_j of the existing patient types and since there are three patient types in this problem instance, there are three different values for μ_j which can be applied to all patient types. Since the transportation factors φ_{jk} are equal in both sets of basic factors for the penalty approach, while the sets of μ_j are different, six values for μ_j are tested.

This set of factors was chosen such that a modification affects both the scenario with and without buses in a positive or not in a negative way and from all those results, those with the shortest durations were chosen. The most promising evacuation transportation plan for both scenarios with and without the availability of buses are generated when the factor μ_2 from the first basic set of penalty factors was given to all patient types. The complete list of penalty factors for this case is given in Table 4.17.

Table 4.17: Equal hospital penalty factors μ_2 in penalty approach

Set 1 with modification	φ_{j1}	φ_{j2}	φ_{j3}	μ_j
Risk group 1 (j=1)	8	16	35	18
Risk group 2 (j=2)	2	3	4	18
Risk group 3 (j=3)	1	1	2	18

Table 4.18 presents the results from the new set of parameter sets in terms of the overall risk and the two durations in comparison to the basic risk minimization, the basic penalty minimization, and the duration minimization both with and without buses.

Table 4.18: Duration and risks: equal hospital penalty factors, ambulances only (a) and ambulances and buses (b)

(a)	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	121	130	19.753
Set 1, basic	119	128	19.7564
Set 1, modified	116	125	21.0009
Duration	113	121	24.187
(b)	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	49	58	9.0451
Set 1, basic	49	56	9.0539
Set 1, modified	46	55	10.1729
Duration	45	52	12.601

These results show that giving every patient the same penalty factor for staying in the hospital for one time interval has a similar effect on the generated evacuation transportation plans as equal threat risks have. The overall risks increase considerably compared to the basic minimizations, but the durations decrease.

Figure 4.21 shows how patients of the different patient types are evacuated when only ambulances are available. There is no separation between patients of different types which is the desired result and similar to the modification with the risk minimization.

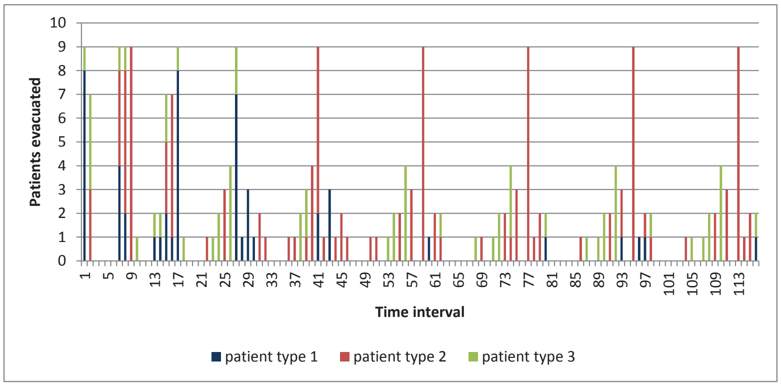

Figure 4.21: Patient evacuation order: penalty approach, modified set 1 of penalty factors, ambulances only

Instead, the assignments of patients to vehicles are very strict. For the scenario that is depicted in Figure 4.21, all of the most critical patients are assigned to the best equipped vehicle type and the least critical patients are all assigned to the second vehicle type. If buses are available for the evacuation transportation, the situation stays the same for the most critical patients who are all assigned to the best equipped vehicle type. The least critical patients are assigned to the second ambulance type and the buses.

Due to the missing separation of patient types in the evacuation order, there is also no specific order in which hospital bed types are filled. The only clear tendency is that the beds in the closest hospitals are filled up early and the beds in the hospitals with a longer routing time are filled up later. This can be see in Figure 4.22 for the scenario without buses.

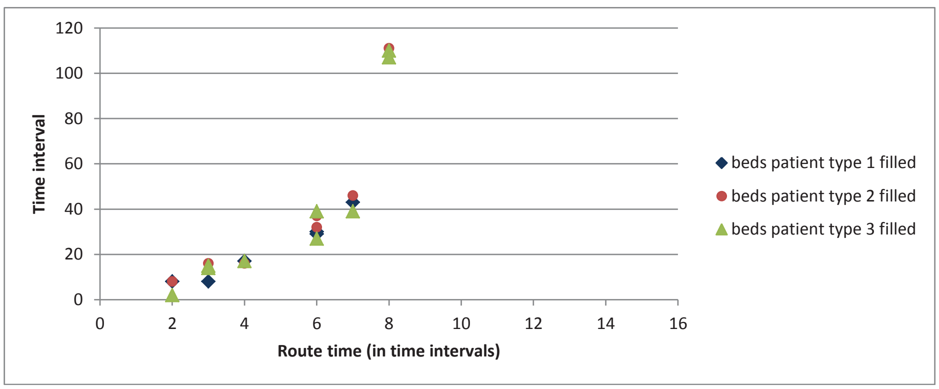

Figure 4.22: Hospital beds: penalty approach, modified set 1 of penalty factors, ambulances only

Figure 4.23 shows the situation when buses are available. The general tendency is not as clear, the outlier results from a bus with patients of the least critical patient type being sent to a hospital with route time 8.

In summary, this sort of modification can also work for the penalty approach and results in shorter durations, a more strict assignment of patients to vehicles, and no separation of patient types in the evacuation order.

The second modification that has desirable effects on the generated evacuation transportation plans with the risk minimization is to increase the transportation risk over time. This can also be implemented for the penalty approach by multiplying the transportation penalty factor φ_{jk} with a factor that incorporates the time interval t of the evacuation. For the modification of the risk functions, the multiplication factors $\frac{t}{T}$ and $2*\frac{t}{T}$ were used. For both

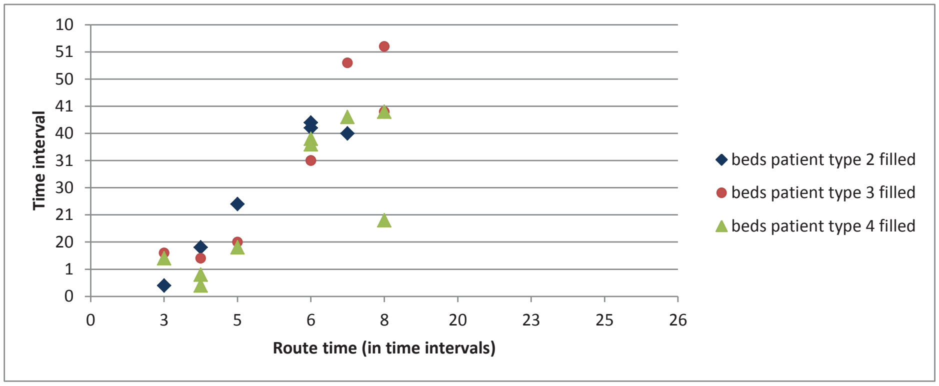

Figure 4.23: Hospital beds: penalty approach, modified set 1 of penalty factors, ambulances and buses

basic factor sets of the penalty approach, those two multiplication factors and $5 * \frac{t}{T}$ were used to take into account that the penalty approach does not show exactly the same results as the risk minimization approach. This means that Φ_{ijk} is now Φ_{ijkt} and is computed as

$$\Phi_{ijkt} = \varphi_{jk} \cdot \frac{t}{T} \cdot (\tau_i + 2 \cdot \gamma_k),\ \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V, t = 1, ..., T \text{ for factor } \frac{t}{T}, \tag{4.4}$$

$$\Phi_{ijkt} = \varphi_{jk} \cdot 2\frac{t}{T} \cdot (\tau_i + 2 \cdot \gamma_k),\ \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V, t = 1, ..., T \text{ for factor } 2\frac{t}{T}, \tag{4.5}$$

$$\Phi_{ijkt} = \varphi_{jk} \cdot 5\frac{t}{T} \cdot (\tau_i + 2 \cdot \gamma_k),\ \forall\ i = 1, ..., H, j = 1, ..., P, k = 1, ..., V, t = 1, ..., T \text{ for factor } 5\frac{t}{T}. \tag{4.6}$$

The advantage of this modification is that patients are considered to be different in terms of their stay in the evacuating hospital as well as in terms of the transportation. The following Table 4.19 presents the two durations and the overall risk for the basic risk minimization, the duration minimization, and for the basic penalty approach with the basic factors, the basic factor set 1 with a multiplication factor $2\frac{t}{T}$, and with the basic factor set 2 with a multiplication factor $\frac{t}{T}$ for both a scenario with only ambulances and a scenario with the use of buses.

The multiplication factors for the results presented in Table 4.19 were chosen from the different multiplication factors for each set as the ones with the shortest durations for both scenarios. Table 4.20 shows the assignments of patients to the different vehicle types for the scenarios with and without the availability of buses. It is noticeable that there are more of

Table 4.19: Duration and risks: increasing transportation penalty, ambulances only (a) and ambulances and buses (b)

(a)	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	121	130	19.753
Set 1, basic	119	128	19.7564
Set 1, $2\frac{t}{T}$	114	123	19.7922
Set 2, basic	118	127	19.7858
Set 2, $\frac{t}{T}$	115	124	19.8244
Duration	113	121	24.187
(b)	Interval last pickup	Interval last delivery	Overall risk
Risk, basic	49	58	9.0451
Set 1, basic	49	56	9.0539
Set 1, $2\frac{t}{T}$	49	56	10.0258
Set 2, basic	47	56	9.0628
Set 2, $\frac{t}{T}$	48	57	10.6004
Duration	45	52	12.601

the most critical patients assigned to vehicles that are not the best equipped ones than there are in the basic penalty case.

Table 4.20: Vehicle assignments: penalty approach with increasing transportation penalty without and with buses, (a): basic factor set 1 with multiplication factor $2\frac{t}{T}$, (b): basic factor set 2 with multiplication factor $\frac{t}{T}$

(a)	P1/V1	P1/V2	P1/V3	P2/V1	P2/V2	P2/V3	P3/V1	P3/V2	P3/V3
Amb.	33	17	-	58	71	-	27	34	-
Bus	22	12	16	21	24	84	13	28	20
(b)	P1/V1	P1/V2	P1/V3	P2/V1	P2/V2	P2/V3	P3/V1	P3/V2	P3/V3
Amb.	34	16	-	60	69	-	22	39	-
Bus	22	6	22	15	27	87	19	31	11

The separation of patient types in the evacuation order remains strict in comparison to the basic penalty case: the last patient of the most critical type leaves the hospital before the last patient of the middle critical patient type and the last patient of the least critical patient type leaves at the end of the evacuation. One example for this can be seen in Figure 4.24 for the penalty minimization with the basic set 1 of penalty factors with the transportation multiplication factor $2\frac{t}{T}$ for the scenario without buses. The same tendency is also true for the penalty minimization with the basic set 2 of penalty factors with the multiplication factor

$\frac{t}{T}$ and also for both of those when buses are available for the evacuation transportation.

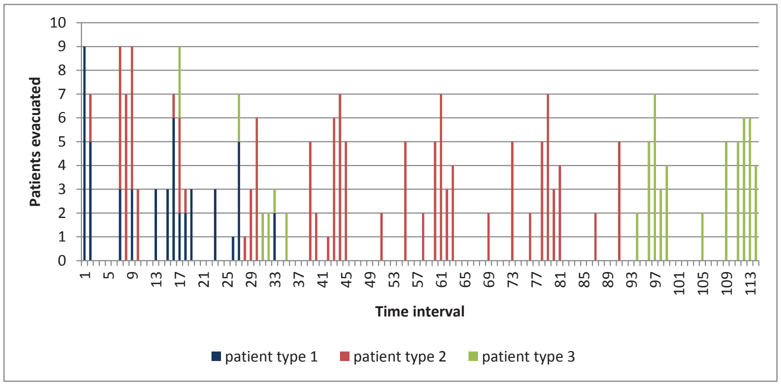

Figure 4.24: Patient evacuation order: penalty approach, set 1 of penalty factors with transportation multiplication factor $2\frac{t}{T}$, ambulances only

Due to those results, the hospital beds of the most critical patient type are also in tendency filled earlier than those of the middle or least critical patient type. As an example for this, Figure 4.25 shows when hospital beds are filled up for the basic set 2 of penalty factors with the transportation multiplication factor $\frac{t}{T}$. It also shows a tendency to fill up the closest hospitals first. If buses are available, the tendencies are also true.

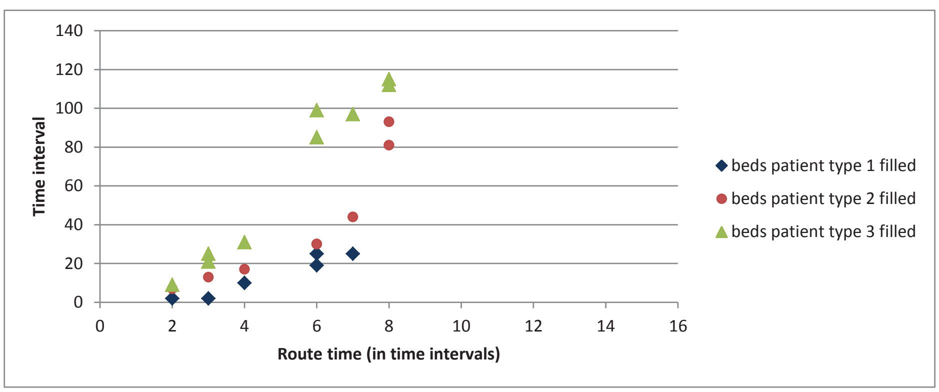

Figure 4.25: Hospital beds: penalty approach, set 2 of penalty factors with multiplication factor $\frac{t}{T}$, ambulances only

In general, this modification also works with the penalty approach. The durations for scenarios without buses are shorter than those for the basic penalty approach, but it does not work as well when buses are available. The separation of patient types for the evacuation order remains valid, but there are more of the most critical patients who are transported in vehicles that are not the best equipped ones.

4.3.3 Alternative Formulation and Computational Effort

This subsection focuses on an alternative formulation of the objective function and the computational effort required for the penalty approach compared to the risk minimization and the duration minimization.

The formulation of the objective function in the penalty minimization approach depends on the pre-computation of the hospital penalty M_{jt}, the transportation penalty Φ_{ijk}, and the overall penalty Ω_{ijkt}. It is, however, also possible not to use pre-computation and to include the computation of the overall penalty, that is, the computation of the hospital penalty and the transportation penalty, into the objective function. The objective function is then

$$Minimize \sum_{i=1}^{H} \sum_{j=1}^{P} \sum_{k=1}^{V} \sum_{t=1}^{T} x_{ijkt} \cdot (\varphi_{jk} \cdot (\tau_i + 2 \cdot \gamma_k) + \mu_j \cdot (t-1)). \tag{4.7}$$

For both basic sets of penalty factors, the approach with the pre-computation and the approach with the extended objective function were tested for both the scenario without and with buses to compare the computational effort. Every optimization for this thesis was run on a Dell Precision T7500 Workstation (24 GB RAM and 2 Intel Xeon E5620 with 2.4 GHz each) with IBM ILOG CPLEX Optimization Studio Version 12.5.

For the first set of basic penalty factors, the run time for the scenario without buses is about 3.8s for both the regular run as well as for the extended objective function. For the scenario with buses, the run takes shortly under 8s for both types of objective functions. For the second set of basic penalty factors, the run time for the scenario with only ambulances is approximately 5s for both the regular run as well as the extended objective function, with buses it is about 7.7s, also for both cases. It is possible that differences start to occur for larger instance sizes but it is a promising result that it is possible to include the computation of the penalties in the objective function itself. It it also interesting to note that the run time is not only depending on the number of variables as there are more possible solutions if buses are available additionally to the two types of ambulances. The run time is also depending on the set of penalty factors which makes it difficult to find general statements about the run times of this approach.

It is, however, possible to compare the run times of the penalty approach with the used problem instance and the two chosen sets of penalty factors with the risk minimization and the duration minimization. For the risk minimization, the three threat scenarios from Bish et al. (2014) are to be compared as those have different run times. Approximate run times for the given specific situation are compared in Table 4.21.

Table 4.21: Run times for scenarios with and without buses

	Run time ambulances only	Run time ambulances and buses
Risk, constant	$1.6s$	$7.8s$
Risk, linear	$4s$	$8.3s$
Risk, exponential	$5s$	$7.2s$
Set 1, basic	$3.8s$	$7.9s$
Set 2, basic	$5s$	$7.7s$
Duration	$1991s$	$464s$

With only one problem instance, it cannot be argued whether the penalty approach has computational advantages in comparison to the risk minimization, but it is clear that the duration minimization requires higher computational efforts which makes it not a desirable approach for emergency situation in which a solution has to be found fast for possibly large problem instances.

4.3.4 Summary Penalty Approach

Although the penalty approach uses another objective than the risk minimization, it is possible to obtain evacuation transportation plans that are close to those generated with the risk minimization, at least in terms of durations and the overall risks. It is also possible to manipulate the penalty factors of the computation of the transportation penalty in order to generate different evacuation plans that have different properties like a shorter duration. In addition, it is possible to extend the objective function in order to decrease the pre-computation. The risks that were used in Bish et al. (2014) and in this thesis were hypothetical, but it is difficult to determine these risks in reality. It might be even difficult to evaluate the threat situation correctly. The penalty approach does not require precise risk functions, it only requires the penalty factors. Although this might be simpler, it also does not take into account that evacuation managers might find the threat to increase exponentially after a certain time interval.

In a way, the objective function using penalties resembles a value function as described for example in Keeney and Raiffa (1993). The formulation of the overall penalty uses the set of decision variables x_{ijkt} to compute a result which measures the value of the solution under certainty. The objective in this approach is to minimize this value and to choose the decision variables such that the minimal value is reached. In the HETM, there are two objectives which are to transport every patient as safe as possible and to evacuate every patient as fast as possible. Due to the various constraints, those cannot be exactly reached simultaneously and the penalty factors are chosen such that the relations reflect which objective is valued higher for the different patient types.

In summary, the penalty approach is a new way to generate evacuation transportation plans that show some similarity in terms of desirable properties to those generated by the risk minimization strategy.

Chapter 5

Conclusions and Future Research

The purpose of this thesis was to further analyze the evacuation transportation plans generated by the HETM from Bish et al. (2014) as those minimize the overall risk composed from a threat risk that originates in the evacuating hospital and the transportation risk that arises from the transportation of a patient in a certain vehicle to a receiving hospital in a given distance. Those evacuation plans were compared to those generated by an objective function which minimizes the duration of the evacuation.

In this thesis, the key features of the generated plans were therefore discussed based upon a specific problem instance adapted from Bish et al. (2014). Those key features are the separation of patients in the evacuation order and the assignments of patients to vehicle types. Both are not considered when the duration is to be minimized as there were no strict rules on how the patients have to be assigned to the vehicles. This was mainly because the durations were not desirable if there are rules for those assignments. It is, however, possible to change the risk functions for the risk minimization such that the generated plans have shorter durations and still have overall risks that are close to those of the basic risk minimization. Restricting the duration for the evacuation transportation plan in the risk minimization approach with the actual minimal duration (computed with the duration minimization approach) shows that it is possible to obtain evacuation plans with overall risks very close to those of the risk minimization. Since the duration minimization itself is computationally not affordable, the combination of both only demonstrates the theoretical possibilities. Possible ways to change the risk functions are to give every patient the same threat risk or to change the computation of the transportation risk to increase over time.

After evaluating possible options to generate other evacuation transportation plans with the risk minimization approach with changed risk functions, a new approach was introduced which uses penalties instead of hypothetical risk functions. This approach adds up penalties weighted by factors for every time interval a patient is in a certain vehicle or still in the evacuating hospital. The advantage is that it is not necessary to create risk functions for the specific situation. It is, however, still necessary to determine the differences between the patient types and to choose the penalty factors such that those differences are reflected in the proportions of the penalties.

At least for the specific problem instance, it was possible to find a set of factors such that the durations and the overall risk of the generated evacuation transportation plan approximated those of the plans generated by a risk minimization with an assumed constant threat risk. It was also possible to manipulate the plans by adopting the same changes to the penalties and the computation of the transportation penalty that were used for the risk minimization approach. The penalty approach, as well as the risk minimization approach, require considerably less computational effort than the duration minimization approach to solve the problem which can be relevant in real situations.

For evacuation planning managers, the most valuable insight is that it is important to determine the specific situation. If it is most important to minimize the overall risk patients are exposed to, there are ways to find such a plan. If it is most important to be fast, there are trade-offs to be made like the evacuation order and the assignments of patients to vehicle types. In some cases, it might not be relevant which patients are the last ones to be evacuated, it is then possible to be more careful with the assignments of patients to vehicle types and to assign the most critical patients only to the best equipped vehicles. In other cases, it might be important to evacuate the most critical patients as fast as possible and in those cases it is difficult to be that careful with the assignments of the most critical patients to the best equipped vehicles.

In general, the model used in this thesis is still simplified and misses some features. Some ongoing research focuses on the possibility of evacuating multiple hospitals at the same time and on implementing the inner processes of the hospital, that is, the transportation of patients from their hospital bed to the waiting area in front of the hospital. Both of those extensions increase the problem size substantially which makes it all the more important to use an approach that is fast and still produces evacuation plans with desired properties.

Other possible factors to include might be for example even more details about the specific characteristics for the different patient types. The model in the state used in this thesis assumes patients to be available when they are scheduled for evacuation. If the transportation within the hospital is implemented, it is possible to take into account for the fact that it might be more complicated to transport a critical patient with more equipment than patients who could move themselves. Those characteristics might also include different loading times into the vehicles or different uses of the capacity of the vehicle as patients with medical equipment have to be loaded more carefully and might take more than one seat in a bus.

In summary, there are various ways to further refine the Hospital Evacuation Transportation Model in order to make it more flexible and more realistic and the penalty approach might be a step towards a simple but realistic and precise model to generate evacuation transportation plans.

Bibliography

Auf der Heide, E. (2006). "The importance of evidence-based disaster planning." *Annals of Emergency Medicine*, **47 (1)**, pp. 34–49.

Augustine, J. and Schoettmer, J.T. (2005). "Evacuation of a rural community hospital: lessons learned from an unplanned event." *Disaster Management & Response*, **3 (3)**, pp. 68–72.

Bastien, M., Dumas, M., Laporte, J., and Parmentier, N. (1985). "Evacuation risks: a tentative approach for quantification." *Risk Analysis*, **5 (1)**, pp. 53–61.

Bish, D., Agca, E., and Glick, R. (2014). "Decision support for hospital evacuation and emergency response." *Annals of Operations Research*, **221 (1)**, pp. 89–106.

Brown, J. (2004). "Providing emergency care during a power outage: August 2003." *Disaster Management & Response*, **2 (1)**, pp. 20–23.

Chalmet, L., Francis, R., and Saunders, P. (1982). "Network models for building evacuation." *Fire Technology*, **18 (1)**, pp. 90–113.

Chavez, C.W. and Binder, B. (1996). "A hospital as victim and responder: the Sepulveda VA Medical Center and the Northridge earthquake." *The Journal of Emergency Medicine*, **14 (4)**, pp. 445–454.

Chen, L. and Miller-Hooks, E. (2008). "The building evacuation problem with shared information." *Naval Research Logistics*, **55 (4)**, pp. 363–376.

Childers, A.K., Mayorga, M.E., and Taaffe, K.M. (2014). "Prioritization strategies for patient evacuations." *Health Care Management Science*, **17 (1)**, pp. 77–87.

Childers, A.K., Visagamurthy, G., and Taaffe, K. (2009). "Prioritizing patients for evacuation from a health-care facility." *Transportation Research Record: Journal of the Transportation Research Board*, **2137 (1)**, pp. 38–45.

Choi, W., Hamacher, H.W., and Tufekci, S. (1988). "Modeling of building evacuation problems by network flows with side constraints." *European Journal of Operational Research*, **35 (1)**, pp. 98–110.

Einav, S., Feigenberg, Z., Weissman, C., Zaichik, D., Caspi, G., Kotler, D., and Freund, H.R. (2004). "Evacuation priorities in mass casualty terror-related events: implications for contingency planning." *Annals of Surgery*, **239 (3)**, pp. 304–310.

Franzese, O. and Han, L. (2002). "Using traffic simulation for emergency and disaster evacuation planning." In *81st Annual Meeting of the Transportation Research Board, Washington*.

Golmohammadi, D. and Shimshak, D. (2011). "Estimation of the evacuation time in an emergency situation in hospitals." *Computers & Industrial Engineering*, **61 (4)**, pp. 1256–1267.

Hamacher, H.W. and Tjandra, S.A. (2001). *Mathematical modelling of evacuation problems: A state of art*. Fraunhofer-Institut für Techno-und Wirtschaftsmathematik, Fraunhofer (ITWM).

Han, L.D., Yuan, F., and Urbanik, T. (2007). "What is an effective evacuation operation?" *Journal of Urban Planning and Development*, **133 (1)**, pp. 3–8.

Iserson, K.V. (2013). "Vertical hospital evacuations: a new method." *Southern Medical Journal*, **106 (1)**, pp. 37–42.

Jarvis, J.J. and Ratliff, H.D. (1982). "Note - some equivalent objectives for dynamic network flow problems." *Management Science*, **28 (1)**, pp. 106–109.

Johnson, C. (2006). "Using computer simulations to support a risk-based approach for hospital evacuation." *A Department of Computing Science Briefing*.

Keeney, R.L. and Raiffa, H. (1993). *Decisions with multiple objectives: preferences and value trade-offs*. Cambridge university press.

Leonard, R. (1985). "Mass evacuation in disasters." *The Journal of Emergency Medicine*, **2 (4)**, pp. 279–286.

Manion, P. and Golden, I.J. (2004). "Vertical evacuation drill of an intensive care unit: design, implementation, and evaluation." *Disaster Management & Response*, **2 (1)**, pp. 14–19.

Mills, A.F., Argon, N.T., and Ziya, S. (). "Dynamic Distribution of Casualties to Medical Facilities in the Aftermath of a Disaster."

Ng, M. and Waller, S.T. (2010). "Reliable evacuation planning via demand inflation and supply deflation." *Transportation Research Part E: Logistics and Transportation Review*, **46 (6)**, pp. 1086–1094.

Pursals, S.C. and Garzón, F.G. (2009). "Optimal building evacuation time considering evacuation routes." *European Journal of Operational Research*, **192 (2)**, pp. 692–699.

Schultz, C.H., Koenig, K.L., and Lewis, R.J. (2003). "Implications of hospital evacuation after the Northridge, California, earthquake." *New England Journal of Medicine*, **348 (14)**, pp. 1349–1355.

Sexton, K.H., Alperin, L.M., and Stobo, J.D. (2007). "Lessons from Hurricane Rita: the University of Texas Medical Branch Hospital's evacuation." *Academic Medicine*, **82 (8)**, pp. 792–796.

Taaffe, K., Johnson, M., and Steinmann, D. (2006). "Improving hospital evacuation planning using simulation." In *Proceedings of the 2006 Winter Simulation Conference*. Winter Simulation Conference, pp. 509–515.

Taaffe, K.M., Kohl, R., and Kimbler, D.L. (2005). "Hospital evacuation: issues and complexities." In *Proceedings of the 2005 Winter Simulation Conference*. IEEE, pp. 943–950.

Tayfur, E. and Taaffe, K. (2009a). "Simulating hospital evacuation - the influence of traffic and evacuation time windows." *Journal of Simulation*, **3 (4)**, pp. 220–234.

Tayfur, E. and Taaffe, K. (2009b). "A model for allocating resources during hospital evacuations." *Computers & Industrial Engineering*, **57 (4)**, pp. 1313–1323.

Tufekci, S. and Kisko, T.M. (1991). "Regional evacuation modeling system (REMS): a decision support system for emergency area evacuations." *Computers & Industrial Engineering*, **21 (1)**, pp. 89–93.

Wabo, N.C., Örtenwall, P., and Khorram-Manesh, A. (2012). "Hospital evacuation; planning, assessment, performance and evaluation." *Journal of Acute Disease*, **1 (1)**, pp. 58–64.